

STUDY OF CURRENT CONTROL INVERTER FED INDUCTION MOTOR DRIVES

Central Library
I. I. T. Kanpur

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

570801

by

VIJAY PRATAP SINGH

to the

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

MAY, 1988

GENTRAL LIBRARY
I , Kanpur.

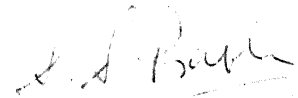
acc. No. **A103077**

“ एक प्रयास !

मन्मीं और पापा के चरणों में ”

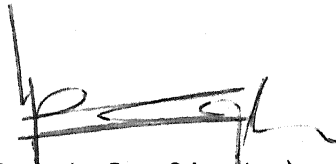
CERTIFICATE

certified that the work entitled 'STUDY OF CURRENT CONTROL
INVERTER FED INDUCTION MOTOR DRIVES' which is being
submitted by Mr. Vijay Pratap Singh in partial fulfilment
of the award of the degree of Master of Technology, has
been carried out under our supervision and guidance. The
matter presented in this thesis, has not been submitted
anywhere for a degree.



(Dr. S.S. Prabhu)
Professor

Department of Electrical Engineering
Indian Institute of Technology
Kanpur



(Dr. L.P. Singh)
Professor

ACKNOWLEDGEMENT

I express my deep sense of gratitude to Dr. L.P. Singh, my mentor, without whose able guidance and unwavering support this work would not, perhaps, have seen the light of the day.

With a deep sense of gratitude I wish to express my indebtedness to Dr. S.S. Prabhu for his stimulating discussions, valuable suggestions and proper guidance throughout this thesis work.

I thank both of them for the freedom I enjoyed during my thesis work.

I also wish to thank Dr. A. Joshi for going through my thesis thoroughly and for his valuable suggestions.

I am extremely grateful to Atul, Ajit, Manoj, Ravi, Jyoti, Kishore, Sanjay, Sandeep, Manasvi in general and E-Top/IV in particular, who have rendered invaluable help through thick and thin, and given fantastic peer support at various stages of this work.

I am also thankful to Mr. J.S. Rawat for his excellent and fast typing.

(VAJAY PRATAP SINGH)

ABSTRACT

The ac motors, particularly squirrel cage induction motor, have a number of advantages in comparison to either dc or synchronous motors. However, under certain conditions, a current/frequency controlled induction motor drive operating either as a motor (or as a generator) can exhibit self-sustained oscillations about a steady-state operating point. At the same time the induction motor is a difficult device to model.

Analysis of current control inverter fed induction motor using d-q model has been done. The feasibility of developing controlled current induction motor drives using transfer function techniques has also been studied. A systematic study of several controllers in a current source inverter fed induction motor drive and their effects on the dynamic response and stability of the system has been carried out in the present work.

It has been shown, that, the system may or may not be stable for various operating points for a given controller gain. Use of adaptive control has been suggested.

TABLE OF CONTENTS

	Page
LIST OF FIGURES	
LIST OF TABLES	
LIST OF SYMBOLS	
ABSTRACT	
CHAPTER 1 INTRODUCTION	1.1
CHAPTER 2 REVIEW OF EXISTING SPEED CONTROL METHODS FOR INDUCTION MOTOR DRIVES	2.1
2.1 Introduction	2.1
2.2 Speed control of induction motor	2.2
2.2.1 Rotor resistance control	2.3
2.2.2 Injecting voltage in the rotor circuit of wound rotor induction motor	2.5
2.2.3 Variable terminal voltage control	2.5
2.2.4 Variable frequency control	2.6
2.3 The controlled slip static inverter drive	2.8
2.3.1 Theory of variable speed induction motor drive	2.8
2.3.2 Control technique	2.12
CHAPTER 3 MATHEMATICAL MODELLING OF INDUCTION MOTOR DRIVE	3.1
3.1 Introduction	3.1
3.2 Description of the drive	3.1
3.2.1 Converter	3.2
3.2.2 The filter	3.3

	Page
3.2.3 The inverter	3.3
3.3 Modelling of the drive	3.5
3.3.1 Mathematical model of the induction motor for controlled current operation	3.6
CHAPTER 4 ANALYSIS OF CONTROLLED CURRENT INDUCTION MOTOR DRIVE	4.1
4.1 Introduction	4.1
4.2 Steady-state characteristics	4.1
4.2.1 Comparison of performance between current source and voltage source drives	4.2
4.2.2 Linearized model for open-loop operation	4.3
4.2.3 Calculation of transfer function for open-loop drive	4.6
4.2.4 Stability analysis of open loop drive	4.7
4.3 Closed-loop control analysis	4.9
4.3.1 Slip frequency control	4.9
4.3.2 Independent current and slip frequency control using proportional controller	4.11
4.3.3 Independent speed and slip frequency control using proportional controller	4.13
4.3.4 Independent speed and slip frequency control using proportional plus Integral controller	4.16
4.4 EFFECT OF CONTROLLER GAIN ON STABILITY	4.19
4.5 COMPARISON OF TRANSIENT RESPONSE FOR VARIOUS CONTROL METHODS	4.20
CHAPTER 5 CONCLUSION	5.1
APPENDIX I	
APPENDIX II	
APPENDIX III	
APPENDIX IV	
REFERENCES	

LIST OF FIGURES

Fig. No.	Details	Page
2.1	Performance curves of induction motor for different values of rotor resistances	2.14
2.2	Slip power recovery scheme for speed control of induction motor below synchronous speed	2.14
2.3	Speed-torque characteristic of induction motor with slip power recovery control	2.15
2.4	Stator voltage control of induction motor	2.15
2.5	Scheme for variable frequency control of induction motor	2.16
2.6	Speed torque characteristics of induction motor for various values of frequency, f_1 is the rated frequency	2.18
2.7	Control slip drive system	2.17
3.1	Basic controlled current source inverter induction motor drive	3.19
3.2	A three-phase fully controlled rectifier	3.19
3.3	An autosequential current source inverter	3.20
3.4	Inverter gating sequence and resulting line currents	3.20
3.5	Angular relaxation of stator and rotor axis with d-q axis	3.21
3.6	d-q equivalent circuit of a controlled current induction motor drive in the synchronously rotating reference frame	3.22
3.7	Simplified d-q equivalent circuit	3.22

Fig. No.	Details	Page
4.1	Steady state equivalent circuit of C&I fed induction	4.39
4.2	Steady state controlled curve induction motor characteristics	4.39
4.3	Developed torque and stator voltage and current characteristics	4.40
4.4	Flux linkage characteristics	4.40
4.5	Open Loop System	4.41
4.6	Independent current and slip frequency control using proportional controller	4.42
4.7	Independent speed and slip frequency control using proportional controller	4.43
4.8	Independent speed and slip frequency control using proportional plus integral controller	4.44
4.9	Root locus plot for open loop control; slip = 0.03	4.45
4.10	Root locus plot for open loop control; slip = 0.02	4.46
4.11	Root locus plot of reference speed and slip frequency control; slip = 0.003	4.47
4.12	Root locus plot of reference and slip frequency control; slip = 0.02	4.48

LIST OF TABLES

Table No.	Details	Page
4.1	Comparison of r performance formula between current source and voltage source drives	4.21
4.2	Open loop transfer function $\Delta I_R' / \Delta V_R'$ for uncontrolled operation at $f_e = 50$ Hz	4.22
4.3	Open loop transfer function $\Delta \omega_r / \Delta \omega_e$ for uncontrolled operation at $f_e = 50$ Hz	4.23
4.4	Transfer function $\Delta I_R' / \Delta V_R'$ for slip frequency control at $f_e = 50$ Hz	4.24
4.5	Transfer function $\Delta \omega_r / \Delta \omega_{sl}$ for slip frequency control at $f_e = 50$ Hz	4.25
4.6	Transfer function $\Delta I_R' / \Delta I_R^*$ with independent and input frequency control at $f_e = 50$ Hz	4.26
4.7	Transfer function $\Delta \omega_r / \Delta \omega_e$ for independent current and input frequency control at $f_e = 50$ Hz	4.27
4.8	Transfer function $\Delta I_R' / \Delta I_R^*$ with independent current and slip frequency control using proportional controller at $f_e = 50$ Hz	4.28
4.9	Transfer function $\Delta \omega_r / \Delta \omega_{sl}$ for independent current and slip frequency control using proportional controller at $f_e = 50$ Hz.	4.29
4.10	Transfer function $\Delta \omega_r / \Delta \omega_r^*$ for independent current and frequency control using proportional controller	4.30
4.11	Transfer function $\Delta \omega_r / \Delta \omega_e$ for independent speed and frequency control using proportional controller	4.31

Table No.	Details	Page
4.12	Transfer function $\Delta\omega_r / \Delta\omega_r^*$ for independent speed and frequency control using proportional controller	4.32
4.13	Transfer function $\Delta\omega_r / \Delta\omega_{sl}$ for independent speed and slip frequency control using proportional controller	4.33
4.14	Transfer function $\Delta\omega_r / \Delta\omega_r^*$ with independent speed and frequency control using PI controller	4.34
4.15	Transfer function $\Delta\omega_r / \Delta\omega_e$ with independent speed and input frequency control using PI controller	4.35
4.16	Transfer function $\Delta\omega_r / \Delta\omega_r^*$ with independent speed and slip frequency control using PI controller	4.36
4.17	Transfer function $\Delta\omega_r / \Delta\omega_{sl}$ with independent speed and slip frequency control using PI controller	4.37
4.18	Comparison of transient response for various control methods ; $K_1 = 1.3$, $K_2 = 1$, $\tau = 0.1$	4.38

LIST OF SYMBOLS

Subscripts

O	steady state quantity as in i_{dro}^e , orthogonal,
d or q	equivalent 2-phase transformed variable as in i_{ds}^e
b	base quantity as in ω_b ,
e	electrical quantity as in ω_e ,
F	smoothing choke parameters as in R_F' ,
I	inverter quantity as in V_I ,
m	mutual value as in x_m ,
l	leakage quantity,
r	rotor quantity as in x_r ,
R	rectifier quantity as in V_R ,
s	stator quantity as in x_s , slip,
sl	slip quantity as in ω_{sl} ,
g	air-gap,
av	average,
max, m	maximum
C	dissipation
mech	mechanical,
a	phase a,
b	phase b,
c	Phase c,
park	Transformed variable
L	Load.

Superscripts

*	command values as in ω_r^* ,
'	rotor quantity referred to the stator,
e	quantities in synchronously rotating reference frame as i_{dr}^e .

Variables

N	effective turns,
r	resistance,
L_l	leakage inductance,
L	self-inductance,
x	Reactance,
Z	impedance,
f	frequency,
K_w	winding factor,
ϕ	Flux,
ω_{sl}	slip speed,
ω	electrical angular speed,
I	current,
V	dc voltage,
T	Torque,
α	firing angle,
θ	Instantaneous angular displacement of the arbitrary reference frame,
θ_r	Angular displacement between the stator and rotor phases,
f	Represents either voltage, current or flux linkage,
n	number of phases,

λ	Total flux-linkages of a particular winding,
L_{sm}	Mutual inductance between stator phases,
L_{rm}	Mutual inductance between rotor phases,
L_{sr}	The amplitude of the mutual inductance between stator and rotor windings,
	perturbation variable,
τ	current regulator zero location,
J	system inertia,
K_1	current regulator gain,
K_2	Speed regulator gain,
p	differential operator d/dt ,
P	machine poles, power,
Q	output of integral controller,
\cong	Approximately equal to,
L_F	filter inductance
R_F	filter resistance
B_r	flux density
\sim	Proportional to

CHAPTER 1

INTRODUCTION

In the past, usually ac motors have been used in the applications requiring constant speed. In variable speed applications, mainly dc motors, especially of shunt type, have been used. The development of power electronic devices, first the thyristor and more recently the gate turn-off thyristor (GTO) and the power transistor has freed ac electronic motors from this constraint of a fixed (i.e. synchronous) speed. With the improvement in capabilities and reduction in cost of these devices, it has become possible to build ac drives which can match dc drives in performance as well as in cost. As a result of this, ac drives have succeeded in replacing dc drives in a number of variable speed applications.

The ac drives compete directly and favourably with the traditional dc drives and they can provide superior performance, faster response, greater bandwidth and greater overload capability. These features are particularly attractive to the machine tool industry and it is in this area that the greatest technical advances has been made. It is possible now to make very simple, rugged and relatively inexpensive ac drives and these have brought the advantages of variable speed to operations such as water and sewage pumping system which could not justify the cost of traditional dc drives.

The ac motors, particularly squirrel cage induction motor, have a number of advantages in comparison to either dc or synchronous motors. Some of these are, lower maintenance, cost, weight, volume and inertia, ruggedness, higher efficiency and improved reliability. The squirrel cage induction motor, having no sliding contacts, can be totally enclosed and, if need be, made flameproof. It can be employed in hazardous and hostile environments. The major drawback of dc motors is the presence of commutator brushes and sliding contact between them, which require frequent maintenance and repair and this makes dc motors unsuitable for explosive and unhealthy environment.

Inverters permit the generation of three-phase ac over a wide range of power frequencies. Most inverters in present use can be designated controllable-voltage adjustable-frequency source, since the output terminal voltage is essentially independent of current. Recently, however, the useful features of inverters in which the current rather than voltage appears essentially as the independent variable, have been recognized. Since a larger portion of electrical equipment which utilizes ac power over a range of frequencies requires current of approximately constant magnitude, this type of inverter appears to have inherent advantages. Typical applications include ac motor drives which are controlled to develop constant motor torque over a fixed speed range. In addition, the current source inverter (CSI) has many advantages which make it an attractive alternative to conventional controllable-voltage source inverters.

The CSI is a very rugged supply capable of recovery from short circuits or commutation faults. It offers inherent overcurrent protection when current feedback is used. It is a simple circuit which does not require fast turnoff thyristors. The CSI is capable of full regeneration with only 12 SCR's and 6 diodes. While it produces a square wave current supply, the motor voltage and hence flux is quasi-sinusoidal. It is cheap and simple to design current source inverter. These numerous advantages have resulted in increasing use of the current source inverter drives.

However, under certain conditions, a current/frequency controlled induction motor drive operating either as a motor or as a generator can exhibit self-sustained oscillations about a steady-state operating point. These oscillations are actual instantaneous rotor speed changes accompanied by variations in output torque, motor current and input power. This operating point instability is directly related to the machine, load and other system parameters. The open-loop operation of current source inverter fed induction motor is unstable for most operating conditions and therefore control loops must be added to realize feasible operating points. For these drives, feedback loops are added for improved regulation and response and also for protection purposes. The presence of open-loop instability, makes design of the closed-loop control by purely laboratory techniques, a

difficult task. All this has prompted us to go into the causes, method of analysis and means of eliminating this instability problem. We will study an analytical design technique for finding the transfer function between a specific input command and a controlled output variable, based on small-signal linearization. In order to assess or design outer control loops such as speed or torque controllers, it is necessary to have a simple but reliable model for the inverter, the induction-motor, and any inner loops which might be considered as basic to the drive. The induction motor is a difficult and complicated device to model because of the many nonlinearities present. Besides, the addition of the inverter power supply adds other non-linearities. Therefore, we will study the systematic development of such a model.

In 1968, BORIS [1] developed theory and control technique for the controlled slip static inverter drive. Later, LIPO and KRAUSE [2,3] in 1969, studied the stability of a rectifier - inverter induction motor drive. They developed a method for determining the stability of a rectifier-inverter induction motor drive system. They also investigated the effect of the system parameters on system stability using Nyquist stability criterion.

The exact equations defining steady-state operation of a controlled current induction motor drive system using state-variable approach were developed by LIPO and CORNELL [4] in 1975.

They showed, that, normal open-loop operation occurs on the unstable side of the torque-slip characteristic necessitating the use of feedback control for stable operation.

SAWAKI and SATO [5] in 1977 studied and compared the steady-state characteristics and instability of an induction motor driven by current source inverter with the system driven by voltage source inverter. They applied Routh-Hurwitz criterion to determine several instability boundaries for various parameters.

A dynamic model for current-controlled induction motor drives was developed by CORNELL and LIPO [6] in 1977. They formulated a transfer function approach to the transient response investigation by means of d-q variables in the synchronously rotating reference frame.

In 1979, SEN [7], studied the various control loops in a current source inverter-induction motor drive and their effects on the dynamic response and stability of the system. The author developed d-q model [8] which incorporates the induction motor and the inverter power supply with current feedback.

The basic idea of the control methods implemented in the present work has been taken from the reference [7] in which various control techniques have been discussed. Faddeeva's method [27] has been used to develop transfer function for various input and output variables.

The present work is organised into five chapters, including the current one, as detailed below.

The Chapter 2 presents a review of various speed control methods of induction motor. Advantages and disadvantages of various speed control methods have also been discussed.

In Chapter 3, a linear model of induction motor for varying frequency of the current source inverter has been developed using d-q variables in the synchronously rotating reference frame. A transformation similar to the Park's transformation, has been used which transforms the motor time-varying equations into time invariant equations.

In Chapter 4, the non-linear equations are linearized about an operating point. Steady state characteristic and stability analysis of an induction motor driven by current source inverter in open loop has been carried out. Analysis of closed loop drive and means of improving stability of these devices has also been done.

Finally, Chapter 5 concludes with the work reported in this thesis and also gives a brief outline of the future scope of work. The report ends with the list of references and books which have been referred in giving shape to this work.

CHAPTER 2

REVIEW OF EXISTING SPEED CONTROL METHODS FOR INDUCTION MOTOR DRIVES

2.1 INTRODUCTION:

The speed of a dc motor cannot be increased much as it is limited by extreme distortion of the air-gap flux of a weak main field caused by armature reaction and consequent poor commutation. The complex constructional features of the dc armature connected to the commutator segments also place an upper limit on the motor speed. Neither of these two limiting factors inhibit the speed of a rugged wound rotor induction motor. On the other hand, ac motors suffer from the inherent speed-constancy of the rotating field dictated by the supply frequency which is normally constant. A wide range of constant speed control is possible only by expensive circuitry using silicon-controlled rectifiers (SCRs). This chapter describes the speed control of induction motors both from rotor and stator sides. Theory and control techniques of the controlled slip static inverter has been described. It is seen that if the slip of an induction motor is constrained and controlled to values below breakdown, the motor operates with high efficiency, high power factor, and moderate current, with performance comparable to that of dc machines [1].

2.2 SPEED CONTROL OF INDUCTION MOTOR:

Various methods of controlling the speed of the induction motor [18] can be visualized by considering the following speed equation

$$\omega = (1-s)\omega_s \quad (2.1)$$

It is seen from equation (2.1), that there are two basic ways of speed control, namely, (i) slip control for fixed synchronous speed and, (ii) control of synchronous speed by suitable methods.

The relationship

$$\omega_s = \frac{2\omega}{P} \quad (2.2)$$

suggests two ways to control the synchronous speed viz., control of supply frequency and change of stator poles. The latter method gives a step control, as poles can be changed in multiples of two. Pole-changing is carried out in a squirrel-cage motor only because of number of poles both for stator and rotor must be the same and that too for two steps. Only a few standard relations [22] which will be referred while discussing speed control methods are given below.

$$I_r = \frac{V_s \angle \theta_s}{(r_s + \frac{r_r'}{s}) + j(x_{ls} + x_{lr}')} \quad (2.3)$$

$$P_g = 3 I_r'^2 \frac{r_r'}{s} \quad (2.4)$$

$$T_{av} = \frac{P_g}{\omega_s} = \frac{3 V_s^2}{\omega_s} \frac{r_r'/s}{(r_s + r_r'/s)^2 + (x_{ls} + x_{lr}')^2} \quad (2.5)$$

$$\frac{r_r}{S_m} \leq \pm \sqrt{r_s^2 + (x_{ls} + x_{lr}')^2} \quad (2.6)$$

$$T_{max} = \frac{3}{2\omega_s} \frac{V_s^2}{r_s \pm \sqrt{r_r'^2 + (x_{ls} + x_{lr}')^2}} \quad (2.7)$$

$$P_c = P_g - P_{mech} = (\omega_s - \omega) T_{av} = S \omega_s T_{av} = S P_g \quad (2.8)$$

and

$$P_{mech} = (1-S) \omega_s T_{av} = (1-S) P_g \quad (2.9)$$

2.2.1 Rotor Resistance Control:

Rotor resistance control [20] involves extracting some energy from the rotor and dissipating it as heat in a resistance so that the power converted into mechanical power is reduced. Thus for the same torque the motor operates at a reduced speed. Speed-torque and speed-rotor current characteristics of the wound-rotor induction motor, for various values of rotor resistance are shown in Fig. 2.1(a) and (b). According to eqn. (2.7) the maximum torque is independent of rotor resistance. However,

according to eqn. (2.6), the slip at which the maximum torque occurs depends upon the rotor resistance. As the rotor resistance is increased, the speed at which the maximum torque occurs decreases i.e. slip increases as shown in Fig. 2.1(a). According to eqn. (2.3) with increase in rotor resistance, the rotor current at a given slip decreases. Thus, with increase in rotor resistance, rotor current, and therefore, the stator current decreases giving higher torque to current ratio. Thus, in drives requiring low speed operation, larger output can be obtained from the machine, thus allowing better use of its capacity. Eqns. (2.5) and (2.3) show that, as the rotor resistance is increased for the same value of torque and rotor current, the machine operates at a lower speed. According to eqns. (2.8) and (2.9), this is achieved by reducing the power developed by the machine (P_{mech}) i.e. shaft power by increasing the power wasted in the rotor resistance. As a result of higher rotor copper loss, the efficiency of the motor is low. Since the copper loss mainly takes place in the external resistances connected to the rotor circuit, it does not cause over-heating of the machine; thus the motor is not derated. This type of speed control is possible only for slip-ring i.e. wound rotor induction motors. This method of speed control can only be adopted in a narrow speed range. Thus, we observe that the rotor resistance control is too inefficient for practical use except for momentary reduction of speed.

2.2 Injecting Voltage in the Rotor Circuit of Wound Rotor Induction Motor:

In this method, a certain fraction of rotor power extracted from the rotor circuit is feedback to the source, instead of being wasted in the resistance as in the case of rotor resistance control. Thus, lesser amount of power transferred to rotor through the air gap is converted into the mechanical power. Hence, for the same torque, machine operates at a lower speed. This scheme is called slip power recovery scheme. The schematic diagram of this scheme is shown in Fig. 2.2. Speed can also be controlled above the synchronous speed but the cost increases. Speed torque characteristic of the induction motor for this scheme is shown in Fig. 2.3. This scheme is used in high power application involving small speed variation below the synchronous speed, such as in high power fan and pump drives.

2.3 Variable Terminal Voltage Control:

This is a slip-control method [22] with constant frequency variable voltage being supplied to the motor stator. Obviously the voltage should only be reduced below the rated value. Speed-torque characteristics of the induction motor for variable values of stator voltage are shown in Fig. 2.4. Fig. 2.4(a) shows the characteristics for low slip induction motor, (motor with low rotor resistance) and Fig. 2.4(b) gives the characteristics for high slip induction motor, (motor with high rotor resistance). It can be seen that speed can be varied by a larger amount when the rotor resistance is high; however, this method can allow speed control only over a small range.

Eqns. (2.3) and (2.5) show that for a given slip, torque is proportional to square of stator voltage and the rotor current is proportional to stator voltage. As the stator voltage is reduced, torque to current ratio decreases. Consequently, for a given thermal loading on the machine, available torque decreases. Low speed operation without overheating is possible if the torque demand on the machine decreases as the speed decreases. Therefore, stator voltage control is suitable for the applications where speed is to be controlled in a limited range only and the load torque decreases with the speed.

Eqns. (2.8) and (2.9) show that with the decrease in speed, rotor copper loss increases but the power converted into mechanical power decreases. The stator voltage control is an inefficient method of speed control. This method of control is commonly used, inspite of poor efficiency and motor derating, because of lower cost compared to alternative methods of speed control such as variable frequency control and slip power recovery scheme.

2.2.4 Variable Frequency Control:

The synchronous speed of the induction motor can be controlled in a stepless way over a wide range by changing the supply frequency [19]. Change in supply frequency varies the synchronous speed, and therefore, speed of the motor. The resultant air-gap flux per pole is given by

$$\phi_r = \frac{1}{4.44 K_w N_s} \left(\frac{V}{f} \right) \quad (2.10)$$

Therefore, in order to avoid saturation and excessive core-loss in stator and rotor cores which would cause sharp increase in magnetization current, the resultant air-gap flux ϕ_r and hence the flux density B_r must be kept constant as frequency is varied. To achieve this, it follows from eqn. (2.10), that, when frequency is varied, voltage must also be varied in such a way that the ratio of the motor terminal voltage and its frequency remains constant. Variable (V,f) supply from constant (V,f) supply can be arranged by the converter-inverter arrangement shown schematically in Fig. 2.5. Speed-torque characteristic for variable frequency control is shown in Fig. 2.6.

Motor speed can also be controlled above the rated speed by increasing the supply frequency above the rated frequency of the machine. Since the terminal voltage cannot be increased beyond the rated value, it is maintained constant at its rated value as the frequency is increased. Thus, speed control above the rated value is obtained with the reduction of the torque capability of the machine.

With variable frequency control, the regenerative braking can easily be obtained throughout its speed range by reducing the frequency in such a way that the synchronous speed at that frequency is lower than the actual motor speed.

Variable frequency control is a highly efficient method of speed control. Due to, high torque to current ratio, it provides fast acceleration and deceleration of the machine. A four quadrant drive can be realized using a variable frequency supply fed squirrel cage induction motor.

2.3 THE CONTROLLED SLIP STATIC INVERTER DRIVE:

The controlled slip static inverter drive [1] uses the versatile characteristic of the semiconductor inverter to achieve optimized control of a squirrel cage induction motor. This technique has been possible during the past few years due to the development of fast, powerful and efficient inverters.

Before any drive system can be applied effectively, the output quantities must be expressed in terms of the output quantities of the controller. These, in turn, must be realized from and related to the controller inputs. We shall now discuss the theory of this drive system.

2.3.1 Theory of Variable Speed Induction Motor Drive:

When balanced polyphase voltages are applied to the symmetric stator windings of an ac machine, a rotating magnetic field is created. A magnetized rotor placed in this field tends to spin in synchronism with this rotating field, thereby forming a synchronous motor. The speed of the motor is dependent on the speed of the field which in turn is a function of the

frequency of the applied voltage. As the frequency is changed to adjust the speed, it is necessary to maintain flux density near some optimum level. In an ac machine, the magnetic flux is related to voltage and frequency in the following manner:

$$\phi_s = \frac{KV}{\omega} \quad (2.11)$$

where K is a constant.

Thus, to control the action of an ac machine, the adjustment of voltage and frequency must be coordinated. If excitation losses and stator voltage drops are neglected, a balanced polyphase voltage $V \sin \omega t$, applied to the symmetric stator windings of a motor, produces a rotating magnetic field in the stator whose angular speed is given by eqn. (2.2) and whose magnitude by eqn. (2.11).

If the speed of the rotor is ω_r , then

$$\omega_{sl} = \omega_s - \omega_r \quad (2.12)$$

The voltage induced in the rotor is

$$V_r \sim \phi_s \omega_{sl} \quad (2.13)$$

The rotor being a closed circuit, the rotor current I_r will be,

$$I_r = \frac{V_r}{Z_r} = \frac{V_r}{\sqrt{r_r'^2 + (\omega_{sl} L_r')^2}}$$

This, in turn produces a flux

$$\phi_r \sim I_r \sim \frac{\phi_s \omega_{sl}}{Z_r} \quad (2.14)$$

This flux lags stator flux ϕ_s by an angle

$$\theta = \frac{\pi}{2} + \tan^{-1} \left(\frac{\omega_{sl} L_{lr'}}{r_r'} \right) = \frac{\pi}{2} + \gamma \quad (2.15)$$

where,

$$\gamma = \tan^{-1} \frac{\omega_{sl} L_{lr'}}{r_r'} \quad (2.16)$$

The motor torque is given by

$$T = \phi_r \phi_s \sin \theta = \phi_r \phi_s \cos \gamma \quad (2.17)$$

Substituting the value of γ from eqn. (2.16) in eqn. (2.17)

we get,

$$T \cong \phi_s^2 \frac{\omega_{sl} r_r'}{Z_r^2} \quad (2.18)$$

$$T \cong \left(\frac{V}{\omega} \right)^2 \frac{\omega_{sl} r_r'}{r_r'^2 + (\omega_{sl} L_{lr'})^2} \quad (2.19)$$

Thus, from eqn. (2.19), we observe that torque depends only on slip ω_{sl} and volts per cycle $\frac{V}{\omega}$.

Differentiating the expression for torque with respect to slip and setting it equal to zero yields

$$\omega_{sm} = \frac{r_r'}{L_{lr'}} \quad (2.20)$$

This is known as the breakdown slip speed associated with the breakdown point (corresponding to the breakdown i.e. maxm. torque).

Operating beyond breakdown slip yields high current, low power factors and high losses. If the slip is constrained and controlled to values below breakdown, high efficiency, high power factor and moderate currents result in an operation comparable to that of a dc machine. Further-more, this holds good even when the speed of the system is varied by adjusting the stator frequency provided that, as in any well designed machine, the flux is kept at a level high enough to obtain good performance, but low enough to control saturation and core losses. The direction of slip relative to the stator determines the direction of power flow, while the voltage determines the level of torque and hence, along with the frequency, the level of power flow.

Thus, eqn. (2.19) is a general expression defining torque involving the quantities of slip speed and excitation. Torque can be controlled by adjusting excitation, or slip, or both in combination. The choice of the particular mode of control depends on the load, the motor type and the controller. The ability to control slip and excitation precisely and accurately depends on the inverter which is used.

Forcing torques, which are a multiple of rated values, can be applied briefly by increasing excitation and/or slip. The resulting increase in losses can be tolerated because of the relatively large thermal time constant of the motor.

2.3.2 Control Technique:

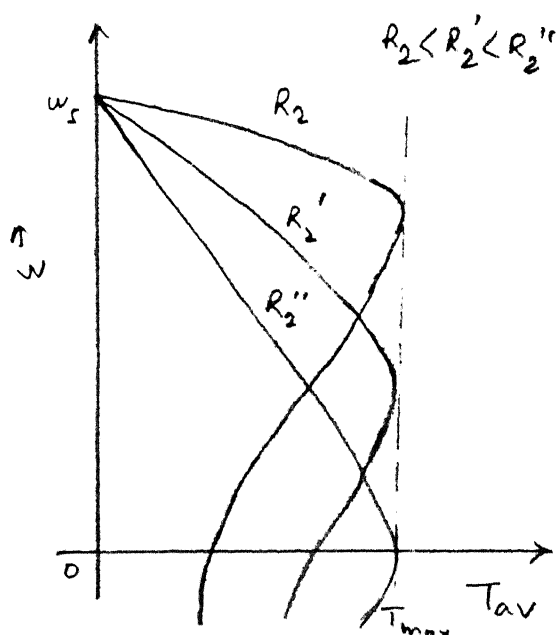
The application of dc drives is normally divided into two classical modes: the constant torque and constant horsepower ranges of operation. In both of the classical operating modes, the essence of the task is to adjust the levels of two interacting fluxes to control speed and torque. In the induction motor, the behaviour of stator flux is analogous to the field of a dc machine. In the constant torque range, stator flux can be maintained by controlling $\frac{V}{\omega}$ and current-slip factors. However, speed is a function of applied frequency and the flux or field 'weakening' is a consequence of operating above base frequency at a fixed voltage as the voltage cannot be increased beyond its rated value.

Flux due to rotor currents is proportional to the product of stator flux and slip. It can be varied to set the torque by adjusting slip and/or excitation, just as the armature flux is controlled by adjusting current in a dc machine. To maintain the maximum value of rotor flux at some level, the slip must be increased as the stator flux is weakened in the constant horsepower mode. A representative control system is shown in Fig. 2.7 which includes a slip control loop and a stator flux regulation brought about by a shaped current reference that produces indirect stator flux control.

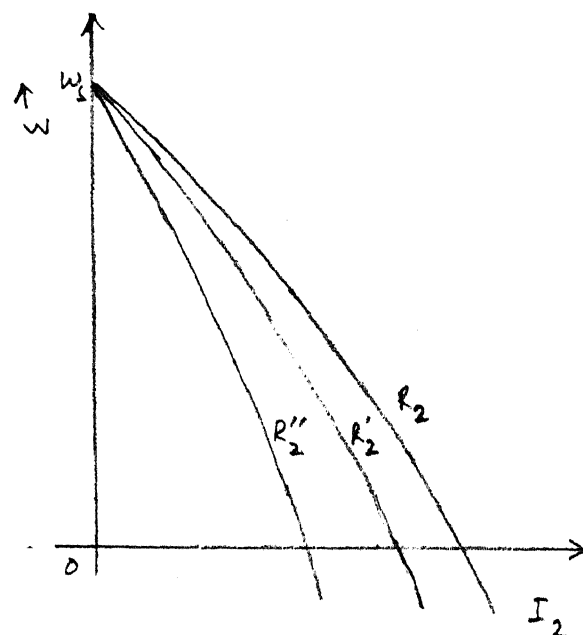
The constant stator flux method is not necessarily optimum, since, in the process of load forcing in the constant torque range, for a given current and speed, the torque is

proportional to the applied voltage squared. This implies that, the excess torque is a function of an excess stator flux at the same maximum rotor flux as measured by stator current. The high flux has the tendency to produce high magnetization losses in steady state in anticipation, so to speak, of the moment when it is necessary to produce brief forcing torque. However, slip losses appear only when the load is being driven.

On the other hand, the essence of harmonics in the waveform, while not affecting increased magnetization losses, does induce rotor losses because their relative slip is high and is virtually unaffected by the speed and loading of the machine. Hence, their contribution to motor loss is roughly proportional to the square of the stator flux. Such losses would soar under conditions of over-excitation. Thus, in the constant torque range, an optimized system can operate with a fixed value of slip. Torque is controlled by adjusting the level of stator flux. Such a system calling for a variable stator flux can also be obtained by forcing that flux with a shaped voltage or flux reference since $T \sim (\frac{V}{\omega})^2 S, \frac{I^2}{S}, \phi_s^2 S$. We will use independent current/speed and/or slip control to study the improvement in the stability of the drive.



(a) Speed-torque curve



(b) Speed-rotor current curve

Fig. 2.1 Performance curves of Induction motor for different values of rotor resistance.

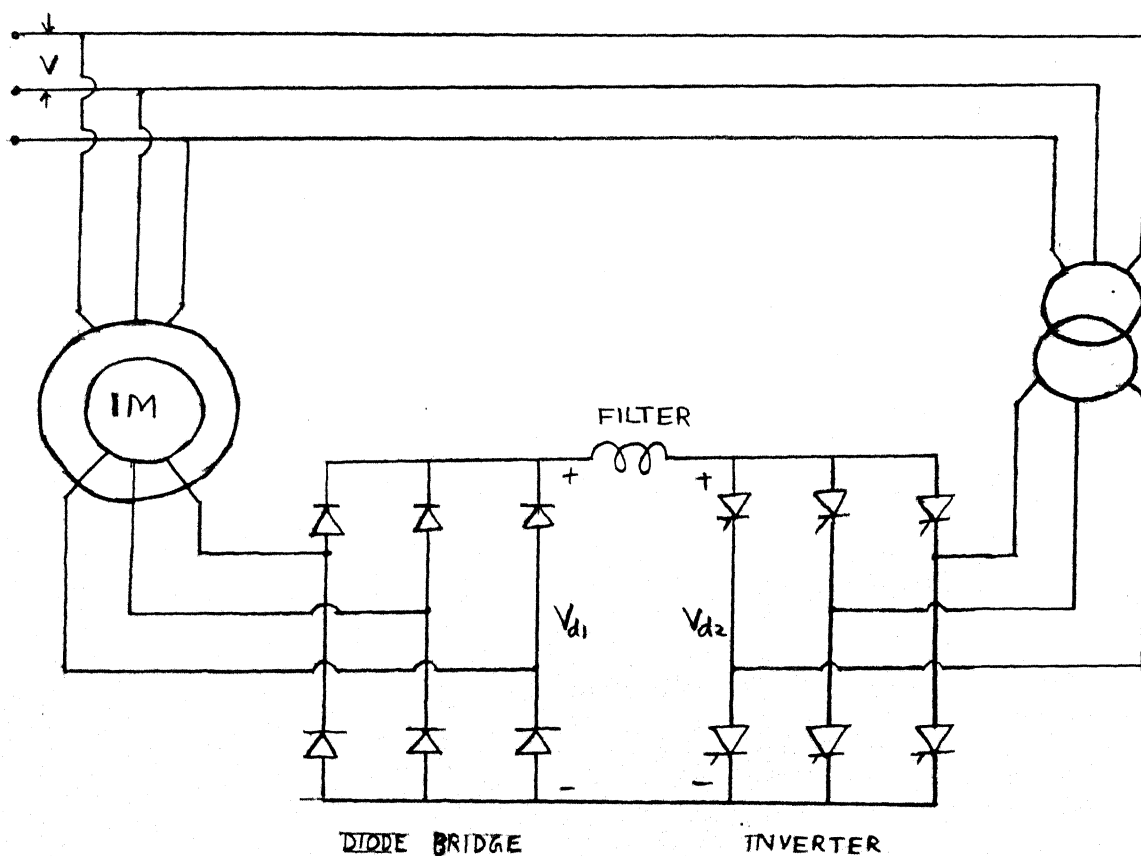


Fig. 2.2 Slip power recovery scheme for speed control of induction motor below synchronous speed.

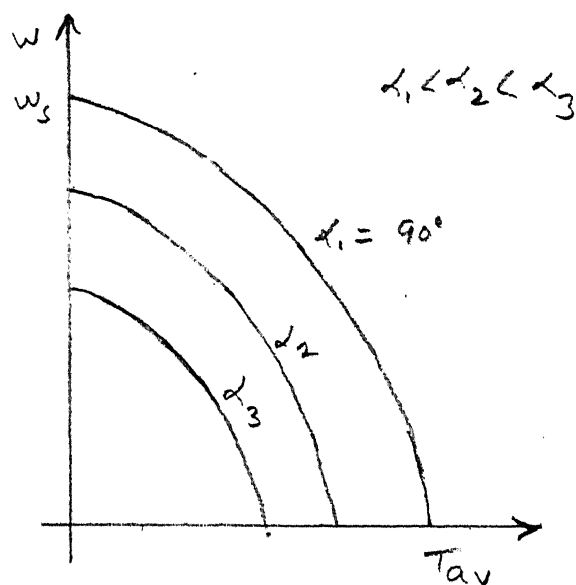
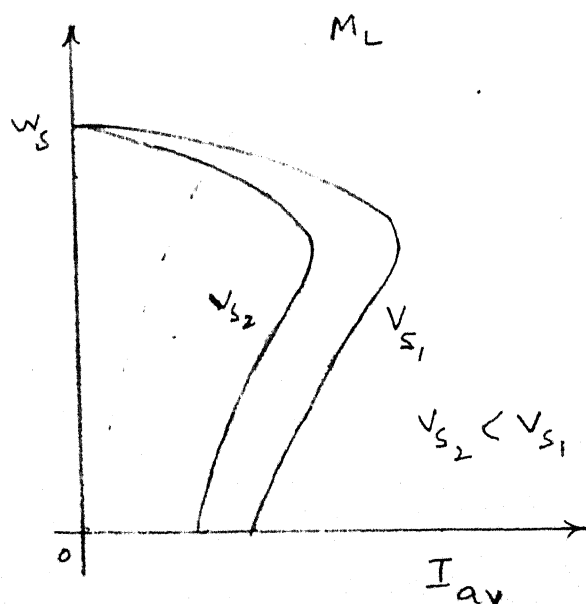
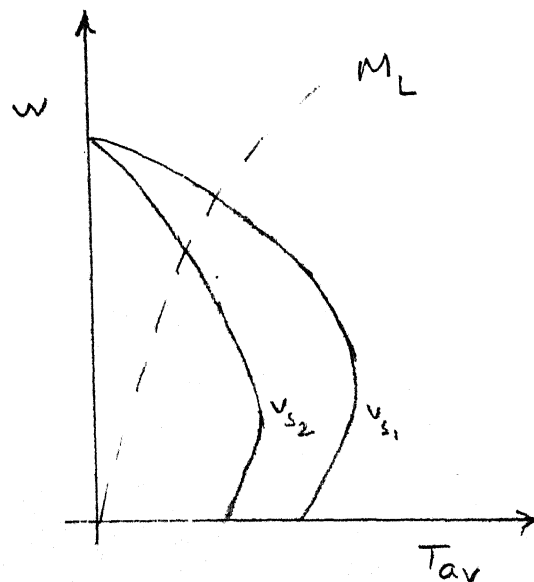


Fig. 2.3 Speed-torque characteristic of induction motor with slip power recovery control.



(a) Low slip induction motor



(b) High slip induction motor

Fig. 2.4 Stator voltage control of induction motor

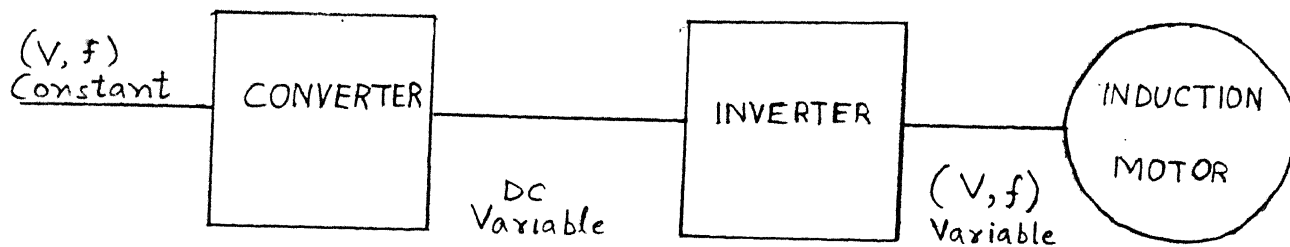


Fig. 2.5 Scheme for variable frequency control of induction motor

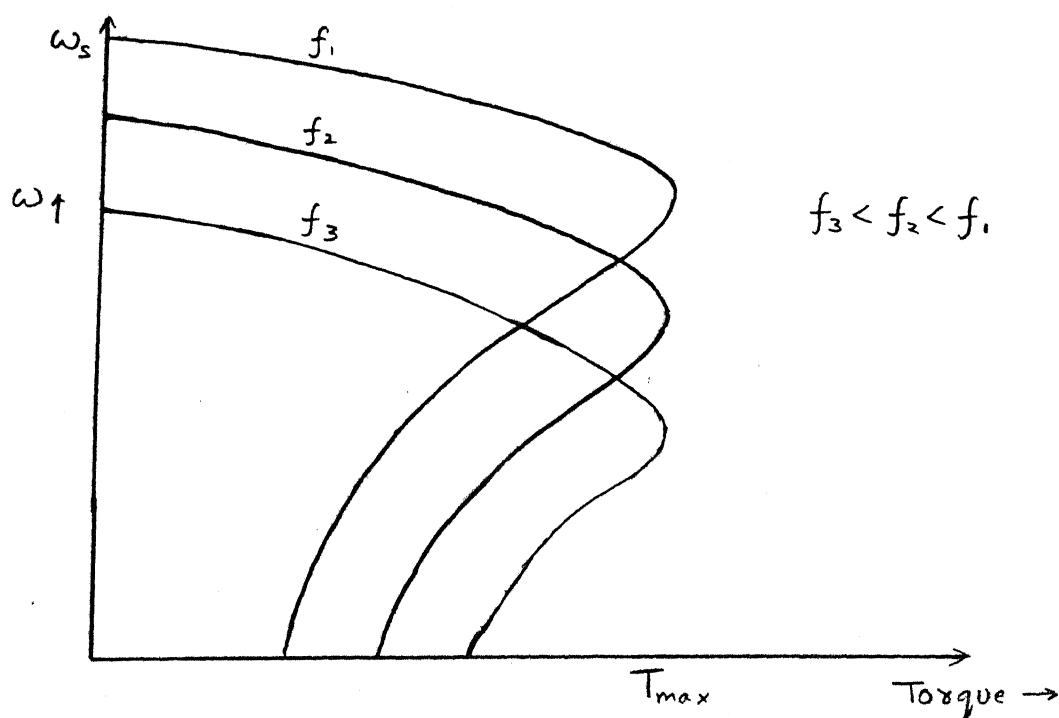


Fig. 2.6 Speed torque characteristics of induction motor for various values of frequencies, f_1 is the rated frequency.

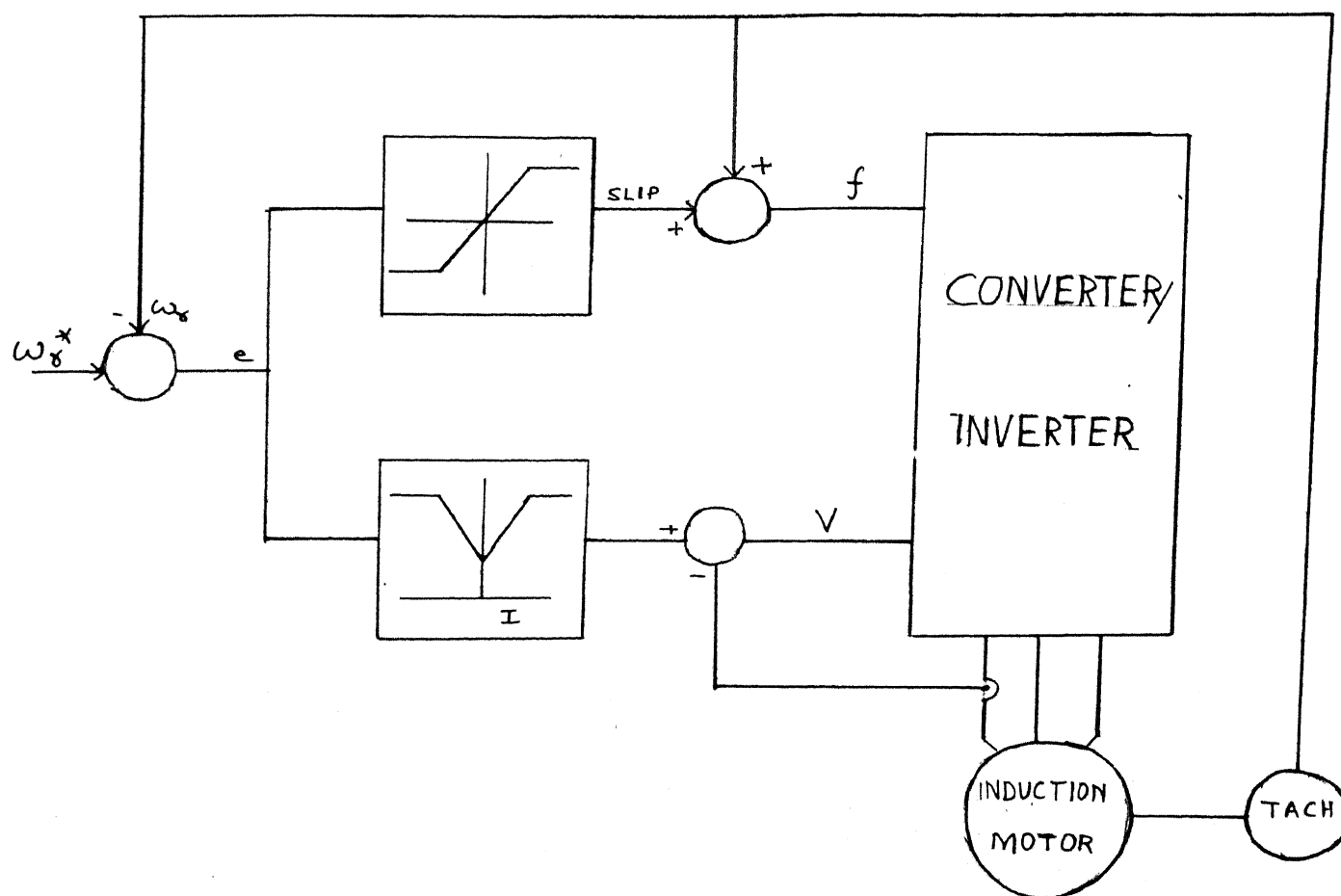


Fig. 2.7 Controlled slip drive system

CHAPTER 3

MATHEMATICAL MODELLING OF INDUCTION MOTOR DRIVE

3.1 INTRODUCTION:

Computer simulation is widely used to study the behaviour of physical systems under various conditions. Appropriate system models are required for digital simulation. In the previous chapter, we described the theory and control technique of variable frequency variable speed induction motor drive. We will now describe the drive configuration in detail. In this chapter, we will develop a suitable model of the induction motor for use in the variable frequency variable speed drive. A complete model of the drive which includes models of the induction motor, converter and inverter has been developed by making suitable assumptions. For the purpose of analysis, we have neglected saturation effects in the motor.

3.2 DESCRIPTION OF THE DRIVE:

Normally an industrial drive draws its power from the standard three-phase system of constant voltage magnitude and fixed frequency. The first requirement is to convert this to dc, the usual instrument for this purpose being the six thyristor bridge rectifier. The dc power is then converted by an inverter to ac power at variable voltage and frequency for application to the motor.

The output voltage of the rectifier has considerable harmonic content, the harmonic frequencies being multiples of six times the supply frequency. The input current to the inverter has also substantial harmonic content, the harmonic frequencies being multiples of six times the inverter output frequency. These two sets of harmonics must be isolated from one another by a filter interposed between the rectifier and the inverter. A simplified diagram of the drive considered is given in Fig. 3.1. We will now describe components of the drive [9].

3.2.1 Converter:

The converter is almost invariably a six thyristor bridge as depicted in Fig. 3.2. This gives six pulse operation, i.e., the output voltage and input current waveforms correspond to six phase operation. The converter of Fig. 3.2 may be directly connected to the three-phase supply or a transformer may be interposed. Direct connection has the merits of lower cost, lower weight and volume (i.e. lesser space) and higher efficiency. Its disadvantages are that, the maximum dc output voltage is dictated by the ac supply voltage and no part of the drive is grounded, the ground being that of the ac supply.

The dc output voltage available from the bridge is given by,

$$V_R = \frac{3\sqrt{3}}{\pi} V_s \cos\alpha \quad (3.1)$$

The voltage level can be varied very rapidly, as far as a drive is concerned almost instantaneously, between the positive and negative maxima by controlling the instants at which the thyristors are switched to the conducting mode. The thyristor converter is a convenient power source for a drive, its major disadvantages being harmonics on both the output and input sides and poor power factor at reduced output voltage.

3.2.2 The Filter:

High efficiency is essential when handling large power so that the only components considered for the filter are capacitors and inductors. Depending on the inverter, the filter may be a large capacitor, an LC low pass combination or an inductor. The so-called current source inverters require an inductor to reduce the current ripple caused by the rectifier harmonics. This is a substantial component with about ten times the inductance of the load. The controlled rectifier bridge and filter together form a dc current source which supplies constant regulated dc current to the inverter.

3.2.3 The Inverter:

The inverter shown in Fig. 3.3 is the autosequential commutated inverter [4]. This is extremely robust and trouble free device which works in the complementary commutation mode, i.e. the incoming thyristor turns off the outgoing thyristor. In Fig. 3.3, thyristors T_1 - T_6 switch the load current at a rate

established by the inverter control and establish the inverter output frequency. Capacitors C_1 - C_6 provide the necessary commutation energy while diodes D_1 - D_6 isolate the capacitors from the load. Ideally, only two phases conduct at any instant of time resulting in six modes of operation.

A diagram illustrating the thyristor gating sequence and resulting line currents is shown in Fig. 3.4. The dc input current is divided among the load phases by the inverter so that the current in each phase has the rectangular waveform.

If I_R is the magnitude of the current in the link, these stepped currents exciting the three stator phases can be represented by the Fourier expansion given by [25],

$$i_{as} = \frac{2\sqrt{3}I_R}{\pi} \left[\cos \omega_e t - \frac{1}{5} \cos 5\omega_e t + \frac{1}{7} \cos 7\omega_e t - \dots \right] \quad (3.2)$$

$$i_{bs} = \frac{2\sqrt{3}I_R}{\pi} \left[\cos(\omega_e t - \frac{2\pi}{3}) - \frac{1}{5} \cos(5\omega_e t + \frac{2\pi}{3}) + \frac{1}{7} \cos(7\omega_e t - \frac{2\pi}{3}) \dots \right] \quad (3.3)$$

$$i_{cs} = \frac{2\sqrt{3}I_R}{\pi} \left[\cos(\omega_e t + \frac{2\pi}{3}) - \frac{1}{5} \cos(5\omega_e t - \frac{2\pi}{3}) + \frac{1}{7} \cos(7\omega_e t + \frac{2\pi}{3}) \dots \right] \quad (3.4)$$

The combination of current source inverter and controlled rectifier readily handles reversal of power flow as from a generating load.

3.3 MODELLING OF THE DRIVE:

The following assumptions are made for the purpose of developing the model of the induction motor drive:

- i) The voltages, currents and impedances are assumed to be symmetric and balanced;
- ii) Commutation overlap is neglected. Switching is considered to be instantaneous and no voltage drop occurring in the thyristors.
- iii) The induction machine is considered to be an ideal symmetric machine in which the stator and the rotor windings are distributed uniformly so as to produce a sinusoidal space distribution of MMF in the air gap.
- iv) Saturation of magnetic core in the induction machine is neglected.
- v) Core losses in induction machine are neglected.
- vi) All parameters of the machine are assumed to be constant.
- vii) The motor is assumed to be a wye-connected three-phase, three-wire system.

Generally, these assumptions do not indicate serious restrictions while they certainly simplify the model. Neglecting harmonics produced by the inverter power supply does not

reduce the significance of the results in terms of stability and transient response. This simplifies the model and enables faster computation of dynamic performance.

3.3.1 Mathematical Model of the Induction Motor for Controlled Current Operation:

When a stator winding is distributed for the purpose of producing a sinusoidal MMF wave in space, it is convenient to portray the winding as an equivalent single coil and express the mutual coupling between it and an equivalent rotor coil as a sinusoidal function of the angular displacement between their magnetic axes. If the induction motor has either a squirrel-cage rotor or a coil wound rotor with the same number of phases (and poles) as the stator, the rotor can be considered as having equivalent coils. The stator windings are identical to each other. Similarly the rotor windings are identical to each other. The line to neutral stator and rotor voltage equations are:

$$[V] = [R] [I] + p[\lambda] \quad (3.5)$$

where,

$$[\lambda]^t = [\lambda_{as} \ \lambda_{bs} \ \lambda_{cs} \ \lambda_{ar} \ \lambda_{br} \ \lambda_{cr}] \quad (3.6)$$

$$[I]^t = [i_{as} \ i_{bs} \ i_{cs} \ i_{ar} \ i_{br} \ i_{cr}] \quad (3.7)$$

$$[V]^t = [v_{as} \ v_{bs} \ v_{cs} \ v_{ar} \ v_{br} \ v_{cr}] \quad (3.8)$$

$$[R] = \begin{bmatrix} r_s & 0 & 0 & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 & 0 \\ 0 & 0 & 0 & r_r' & 0 & 0 \\ 0 & 0 & 0 & 0 & r_r' & 0 \\ 0 & 0 & 0 & 0 & 0 & r_r' \end{bmatrix} \quad (3.9)$$

and p denotes the 'd/dt' operator.

Since, the stator and the rotor windings are 3-phase wire systems, the flux linkage equations [8] are,

$$[\lambda] = [L] [I] \quad (3.10)$$

where,

$$[L] = \begin{bmatrix} L_{ss} & 0 & 0 & L_{sr} \cos \theta_r \\ 0 & L_{ss} & 0 & L_{sr} \cos(\theta_r - \frac{2\pi}{3}) \\ 0 & 0 & L_{ss} & L_{sr} \cos(\theta_r + \frac{2\pi}{3}) \\ L_{sr} \cos \theta_r & L_{sr} \cos(\theta_r - \frac{2\pi}{3}) & L_{sr} \cos(\theta_r + \frac{2\pi}{3}) & L_{rr} \\ L_{sr} \cos(\theta_r + \frac{2\pi}{3}) & L_{sr} \cos \theta_r & L_{sr} \cos(\theta_r - \frac{2\pi}{3}) & 0 \\ L_{sr} \cos(\theta_r - \frac{2\pi}{3}) & L_{sr} \cos(\theta_r + \frac{2\pi}{3}) & L_{sr} \cos \theta_r & 0 \\ L_{sr} \cos(\theta_r + \frac{2\pi}{3}) & L_{sr} \cos(\theta_r - \frac{2\pi}{3}) \\ L_{sr} \cos \theta_r & L_{sr} \cos(\theta_r + \frac{2\pi}{3}) \\ L_{sr} \cos(\theta_r - \frac{2\pi}{3}) & L_{sr} \cos \theta_r \\ 0 & 0 \\ L_{rr} & 0 \\ 0 & L_{rr} \end{bmatrix} \quad (3.11)$$

where,

$$L_{ss} = L_s - L_{sm} \quad (3.12)$$

$$L_{rr} = L'_r - L_{rm} \quad (3.13)$$

Due to the sinusoidal space variation of the mutual inductances with respect to the displacement angle θ_r , time-varying coefficients will appear in the voltage equations. This undesirable feature can be eliminated by a proper change of variables which, in effect, transforms the phasor voltages and currents of both the stator and rotor to a common frame of reference.

Fig. 3.5 shows the angular relation of the stator and rotor magnetic axes of a three-phase machine with the third set which is an orthogonal set (d-q axis) rotating at an arbitrary electrical angular speed ω ($= \frac{d\theta}{dt}$). It is clear that as-bs-cs set is fixed in the stator and ar-br-cr set is fixed in the rotor and hence rotates at an angular velocity of ω_r . The angular relationship between the three sets of axes at time $t=0$, can be selected arbitrarily. However, it is convenient to assume that at time $t=0$, the q axis and the magnetic axes of the stator (as) and rotor (ar) phases coincide [21].

The following power invariant Park's transformation [21], which can be developed based upon symmetries inherent in the machine and using mathematical theory of groups, is considered.

$$T_s = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \quad (3.14)$$

Also,

$$T_R = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\beta & \sin\beta & 1 \\ \cos(\beta - \frac{2\pi}{3}) & \sin(\beta - \frac{2\pi}{3}) & 1 \\ \cos(\beta + \frac{2\pi}{3}) & \sin(\beta + \frac{2\pi}{3}) & 1 \end{bmatrix} \quad (3.15)$$

Then, the transformed equations for the balanced system, which can be correlated to the angular relation of the axes as shown in Fig. 3.5, are as follows,

$$\begin{bmatrix} f_{qs} \\ f_{ds} \\ f_{os} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} \cos\theta & \sqrt{2} \cos(\theta - \frac{2\pi}{3}) & \sqrt{2} \cos(\theta + \frac{2\pi}{3}) \\ \sqrt{2} \sin\theta & \sqrt{2} \sin(\theta - \frac{2\pi}{3}) & \sqrt{2} \sin(\theta + \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix} \quad (3.16)$$

and for rotor,

$$\begin{bmatrix} f_{qr} \\ f_{dr} \\ f_{or} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} \cos \beta & \sqrt{2} \cos(\beta - \frac{2\pi}{3}) & \sqrt{2} \cos(\beta + \frac{2\pi}{3}) \\ \sqrt{2} \sin \beta & \sqrt{2} \sin(\beta - \frac{2\pi}{3}) & \sqrt{2} \sin(\beta + \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} f_{ar} \\ f_{br} \\ f_{cr} \end{bmatrix} \quad (3.17)$$

$$\text{where } \beta = \theta - \theta_r. \quad (3.18)$$

In these equations, variable f represents either voltage, current or flux linkage. These equations are restricted by the condition that the instantaneous angular displacement θ of the arbitrary reference frame must be a continuous time function.

f_{os} and f_{or} are taken because, in general, three independent variables are necessary. If, however, only balanced conditions are to be considered, the third voltage or current can be defined in terms of other two. Hence, a third variable is unnecessary.

Also, if a 3-wire system are analysed, it can be shown that for the balanced system the zero subscripts (f_{os} and f_{or}) are non-existent. So these quantities can be excluded from its equivalent circuit development.

The equation (3.10) can be written as,

$$\begin{bmatrix} \lambda_S \\ \lambda_R \end{bmatrix} = \begin{bmatrix} L_{SS} & L_{SR} \\ L_{SR}^t & L_{RR} \end{bmatrix} \begin{bmatrix} i_S \\ i_R \end{bmatrix} \quad (3.19)$$

where, S refers to stator quantities and R refers to rotor quantities. L_{SR}^t is the transpose of L_{SR} . Using the transformations,

$$[\lambda] = [T] [\lambda_{\text{park}}] \quad (3.20)$$

and

$$[i] = [T] [i_{\text{park}}] \quad (3.21)$$

which define λ_{park} and i_{park} , Equation (3.19) is transformed [23] to,

$$\begin{bmatrix} \lambda_{S(\text{park})} \\ \lambda_{R(\text{park})} \end{bmatrix} = \begin{bmatrix} T_S^{-1} & 0 \\ 0 & T_R^{-1} \end{bmatrix} \begin{bmatrix} L_{SS} & L_{SR} \\ L_{SR}^t & L_{RR} \end{bmatrix} \begin{bmatrix} T_S & 0 \\ 0 & T_R \end{bmatrix} \begin{bmatrix} i_{S(\text{park})} \\ i_{R(\text{park})} \end{bmatrix}$$

$$= \begin{bmatrix} T_S^{-1} L_{SS} T_S & T_S^{-1} L_{SR} T_R \\ T_R^{-1} L_{SR}^t T_S & T_R^{-1} L_{RR} T_R \end{bmatrix} \begin{bmatrix} i_{S(\text{park})} \\ i_{R(\text{park})} \end{bmatrix} \quad (3.22)$$

Finally equation (3.22) reduces to,

$$\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{os} \\ \lambda_{qr} \\ \lambda_{dr} \\ \lambda_{or} \end{bmatrix} = \begin{bmatrix} L_{SS} & 0 & 0 & \frac{3}{2}L_{sr} & 0 & 0 \\ 0 & L_{SS} & 0 & 0 & \frac{3}{2}L_{sr} & 0 \\ 0 & 0 & L_{SS} & 0 & 0 & 0 \\ \frac{3}{2}L_{sr} & 0 & 0 & L_{rr} & 0 & 0 \\ 0 & \frac{3}{2}L_{sr} & 0 & 0 & L_{rr} & 0 \\ 0 & 0 & 0 & 0 & 0 & L_{rr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{os} \\ i_{qr} \\ i_{dr} \\ i_{or} \end{bmatrix} \quad (3.23)$$

Premultiplying both sides of voltage equation (3.5) by T^{-1} , we have

$$T^{-1} [V] = T^{-1} [R] [I] + T^{-1} p[\lambda] \quad (3.24)$$

Thus we obtain, in terms of transformed variables,

$$[V_{\text{park}}] = [R] [I_{\text{park}}] + T^{-1} [p(T[\lambda_{\text{park}}])] \quad (3.25)$$

$$[V_{\text{park}}] = [R][I_{\text{park}}] + T^{-1} (T_p[\lambda_{\text{park}}] + (pT)[\lambda_{\text{park}}]) \quad (3.26)$$

or

$$[V_{\text{park}}] = [R] [I_{\text{park}}] + p[\lambda_{\text{park}}] + T^{-1} pT[\lambda_{\text{park}}] \quad (3.27)$$

Assuming balanced condition (i.e. zero sequence current is zero, and consequently, zero sequence voltage is also zero), and using equation (3.27) for stator and rotor voltages, we get the voltage equation as,

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v'_{qr} \\ v'_{dr} \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 \\ 0 & 0 & r'_r & 0 \\ 0 & 0 & 0 & r'_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i'_{qr} \\ i'_{dr} \end{bmatrix} + p \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda'_{qr} \\ \lambda_{dr} \end{bmatrix} + \begin{bmatrix} \lambda_{ds} & 0 \\ -\lambda_{qs} & 0 \\ 0 & \lambda'_{dr} \\ 0 & \lambda'_{qr} \end{bmatrix} p \begin{bmatrix} \theta \\ \beta \end{bmatrix} \quad (3.28)$$

where,

$$\lambda_{qs} = L_{ls} i_{qs} + M (i_{qs} + i'_{qr})$$

$$\lambda_{dr} = L_{lr} i_{ds} + M (i_{ds} + i'_{dr})$$

$$\begin{aligned}
\lambda'_{qr} &= L'_{lr} i'_{qr} + M(i_{qs} + i'_{qr}) \\
\lambda'_{dr} &= L'_{lr} i'_{dr} + M(i_{ds} + i'_{dr})
\end{aligned} \tag{3.29}$$

and,

$$\begin{aligned}
L_{ls} &= L_{ss} - \frac{3}{2} L_{ms} \\
L'_{lr} &= L'_{rr} - \frac{3}{2} L_{ms} \\
M &= \frac{3}{2} L_{ms} \\
L_{ms} &= \frac{N_s}{N_r} L_{sr}
\end{aligned} \tag{3.30}$$

prime denote rotor quantities referred to the stator side.

Expression for instantaneous electromagnetic torque can be obtained by applying the principle of virtual displacement based upon the concept of virtual work. This relation, which is positive for motor action, is,

$$T_e = \left(\frac{n}{2}\right) \left(\frac{p}{2}\right) M (i_{qs} i'_{dr} - i_{ds} i'_{qr}) \tag{3.31}$$

Using eqns. (3.23), (3.28), (3.29), (3.30) and putting

$v'_{qr} = v'_{dr} = 0$, we get induction machine equations [2] in the matrix form as shown below:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + pL_s & \omega L_s & pM & \omega M \\ -\omega L_s & r_s + pL_s & -\omega M & pM \\ pM & (\omega - \omega_r)M & r'_r + pL'_r & (\omega - \omega_r)L'_r \\ -(\omega - \omega_r)M & pM & -(\omega - \omega_r)L'_r & r'_r + pL'_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i'_{qr} \\ i'_{dr} \end{bmatrix} \tag{3.32}$$

Here, $L_s = L_{ls} + M$

and $L_r' = L_{lr}' + M$ (3.33)

For synchronously rotating reference frame $\omega = \omega_e$, hence the equation (3.29) becomes

$$\begin{bmatrix} v_{qs}^e \\ v_{ds}^e \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + pL_s & \omega_e L_s & pM & \omega_e M \\ -\omega_e L_s & r_s + pL_s & -\omega_e M & pM \\ pM & \omega_{sl} M & r_r' + pL_r' & \omega_{sl} L_r' \\ -\omega_{sl} M & pM & -\omega_{sl} L_r' & r_r' + pL_r' \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ i_{qr}'^e \\ i_{dr}'^e \end{bmatrix} \quad (3.34)$$

where, $\omega_{sl} = \omega_e - \omega_r$

or $\omega_{sl} = \omega_e^S$ (3.35)

The electromagnetic torque for three phase machine is,

$$T_e = \frac{3}{2} \frac{P}{2} M (i_{qs}^e i_{dr}'^e - i_{ds}^e i_{qr}'^e) = T_L + \frac{2J}{P} (p\omega_r) \quad (3.36)$$

The $3/2$ term which appears in the above expression is the result of using a transformation of variables which preserves the input power from phase to d-q quantities.

Using Equation (3.4) and applying the proper equations of transformation (Appendix I), we obtain the corresponding q- and d-axis currents in the synchronously rotating reference frame as shown,

$$i_{qs}^e = \frac{2\sqrt{3}}{\pi} I_R \left(1 - \frac{2}{35} \cos 6\omega_e t - \frac{2}{143} \cos 12\omega_e t - \dots \right) \quad (3.37)$$

$$i_{ds}^e = \frac{2\sqrt{3}}{\pi} I_R \left(-\frac{12}{35} \sin 6\omega_e t - \frac{24}{143} \sin 12\omega_e t - \dots \right) \quad (3.38)$$

For convenience, these currents can be expressed [6] as,

$$i_{qs}^e = I_R' g_{qs}^e \quad (3.39)$$

$$i_{ds}^e = I_R' g_{ds}^e \quad (3.40)$$

where,

$$g_{qs}^e = 1 - \frac{2}{35} \cos 6\omega_e t - \frac{2}{143} \cos 12\omega_e t - \dots \quad (3.41)$$

$$g_{ds}^e = -\frac{12}{35} \sin 6\omega_e t - \frac{24}{143} \sin 12\omega_e t - \dots \quad (3.42)$$

and,

$$I_R' = \frac{2\sqrt{3}}{\pi} I_R \quad (3.43)$$

Assuming no power loss in the inverter, the power into and out of the inverter is identical, so that we get,

$$V_I I_R = \frac{3}{2} (v_{qs}^e i_{qs}^e + v_{ds}^e i_{ds}^e) \quad (3.44)$$

The inverter voltage is obtained by combining eqns. (3.39), (3.40) and (3.44) as,

$$V_I = \frac{3\sqrt{3}}{\pi} (v_{qs}^e g_{qs}^e + v_{ds}^e g_{ds}^e) \quad (3.45)$$

or,

$$V_I' = v_{qs}^e g_{qs}^e + v_{ds}^e g_{ds}^e \quad (3.46)$$

where,

$$V_I' = \frac{\pi}{3\sqrt{3}} V_I \quad (3.47)$$

Assuming continuous current in the smoothing reactor, the quantities I_R' and V_I' can be viewed as normalized dc link variables referred to the d-q axes.

The differential equation expressing the dc link variables is expressed in terms of normalized quantities [6] as,

$$V_R' = V_I' + (R_F' + pL_F')I_R' \quad (3.48)$$

where,

$$R_F' = \frac{\pi^2}{18} R_F \quad (3.49)$$

$$L_F' = \frac{\pi^2}{18} L_F \quad (3.50)$$

and,

$$V_R' = \frac{\pi}{3\sqrt{3}} V_R \quad (3.51)$$

Using equations (3.34), (3.39), (3.40), (3.46) and (3.48), we obtain the d-q equivalent circuit of a current controlled induction motor drive in the synchronously rotating reference frame as shown in Fig. 3.6.

Although, the actual system operates with rectangular wave excitation from a high equivalent impedance source, it is

well known that the machine stability is determined primarily by the fundamental components of machine variables. If the effects of harmonics is neglected, then, we have,

$$g_{qs}^e \cong 1.0 \quad (3.52)$$

$$g_{ds}^e \cong 0, \quad (3.53)$$

whereby, from eqn. (3.39) and eqn. (3.40)

$$i_{qs}^e = I_R' \quad (3.54)$$

$$i_{ds}^e = 0. \quad (3.55)$$

Thus, we observe that the current in the stator q-axis, I_R' , corresponds to the peak value of the fundamental component of motor phase current. The d-axis stator current is identically zero during both steady-state and transient conditions due to the positioning of the synchronously rotating reference frame axes.

Also, equation (3.46) reduces to

$$V_I' = v_{qs}^e \quad (3.56)$$

with v_{ds} assuming the open-circuit value resulting from mutual coupling.

By neglecting harmonics, the detailed equivalent circuit of Fig. 3.6 reduces to the simplified equivalent circuit shown in Fig. 3.7.

Combining equations (3.54) and (3.55) with the equations of the induction machine in the synchronously rotating reference frame, we get the drive equations as

$$\begin{bmatrix} V_R' \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + R_F' + p(L_S + L_F') & pM & \omega_e M \\ pM & r_r' + pL_r' & \omega_{sl} L_r' \\ -\omega_{sl} M & -\omega_{sl} L_r' & r_r' + pL_r' \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{qr}^e \\ i_{dr}^e \end{bmatrix} \quad (3.57)$$

and,

$$T_e = \frac{3P}{4\omega_b} M i_{qs}^e i_{dr}^e = T_L + \frac{2J}{P} p\omega_r \quad (3.58)$$

We will use the non-linear eqns. (3.57) and (3.58) to develop the linearized model of the drive in the next chapter.

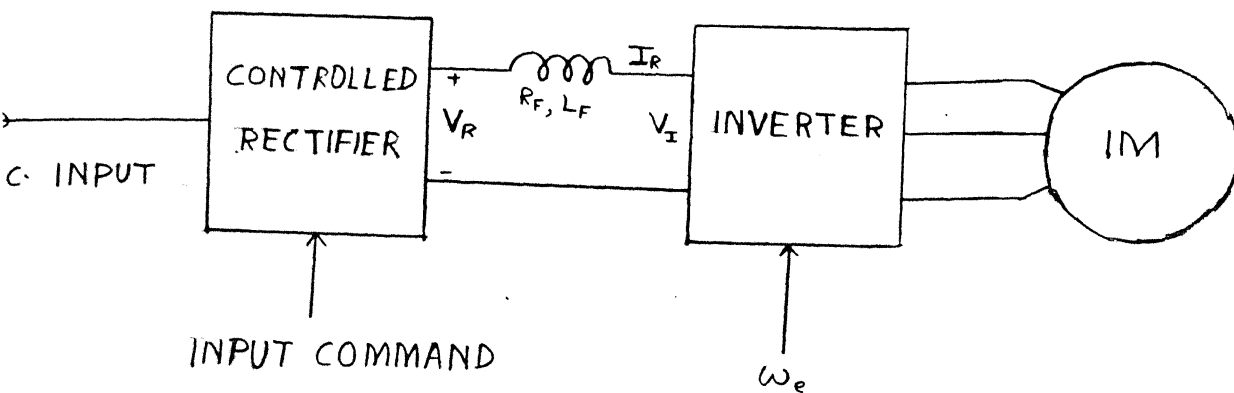


Fig. 3.1 Basic controlled current source inverter induction motor drive.

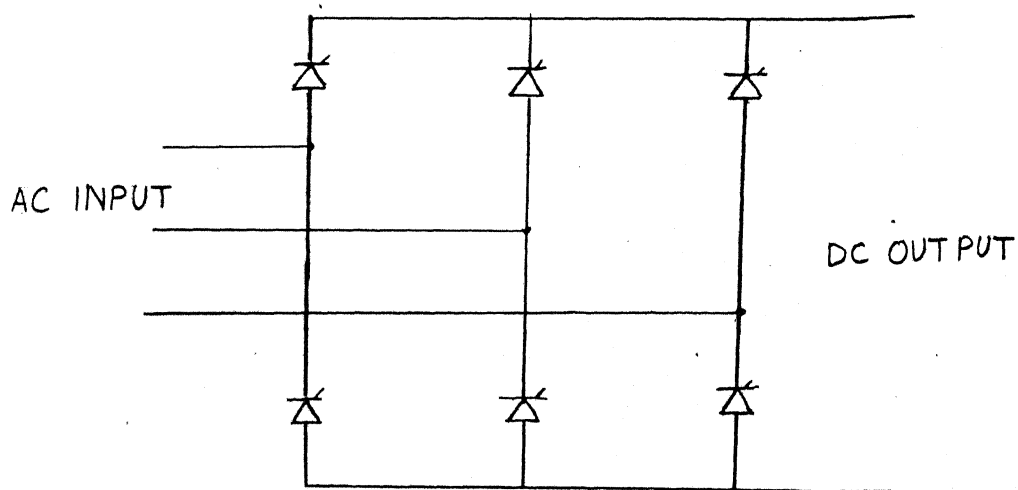


Fig. 3.2 A three-phase fully controlled rectifier

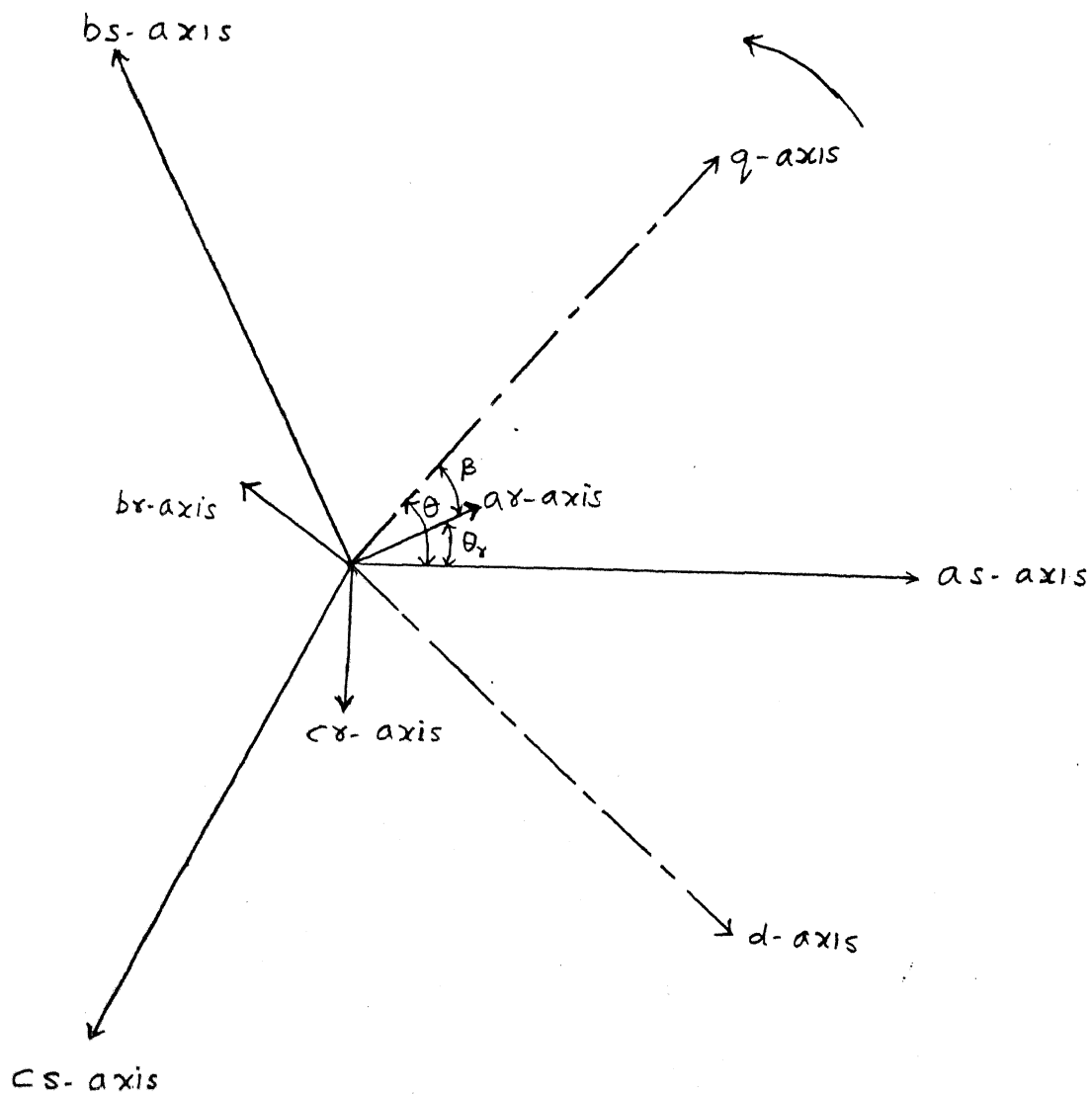


Fig. 3.5 Angular relation of stator and rotor axis with d-q axis.

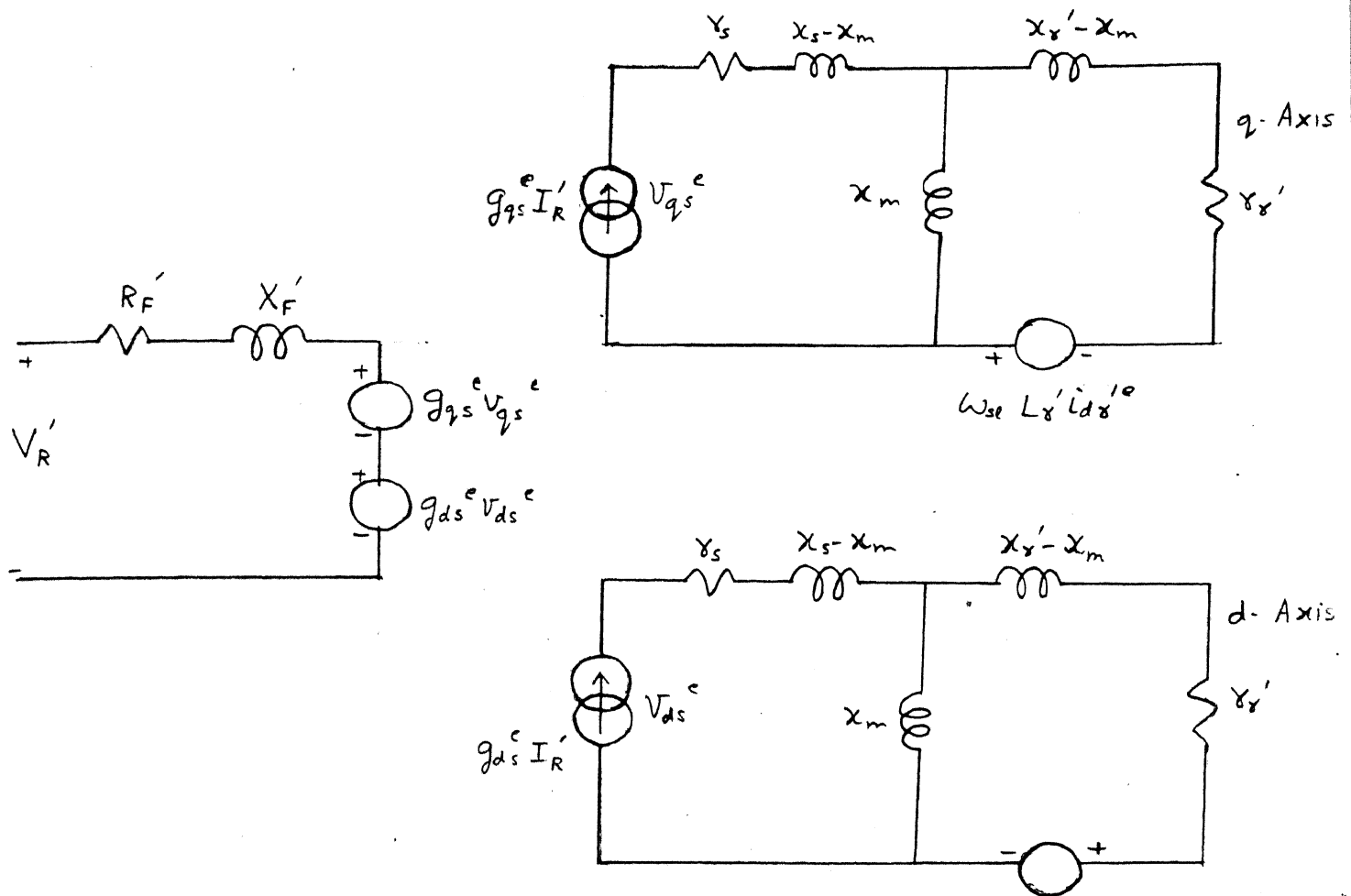


Fig. 3.6 d-q equivalent circuit of a controlled current induction motor drive in the synchronously rotating reference frame.

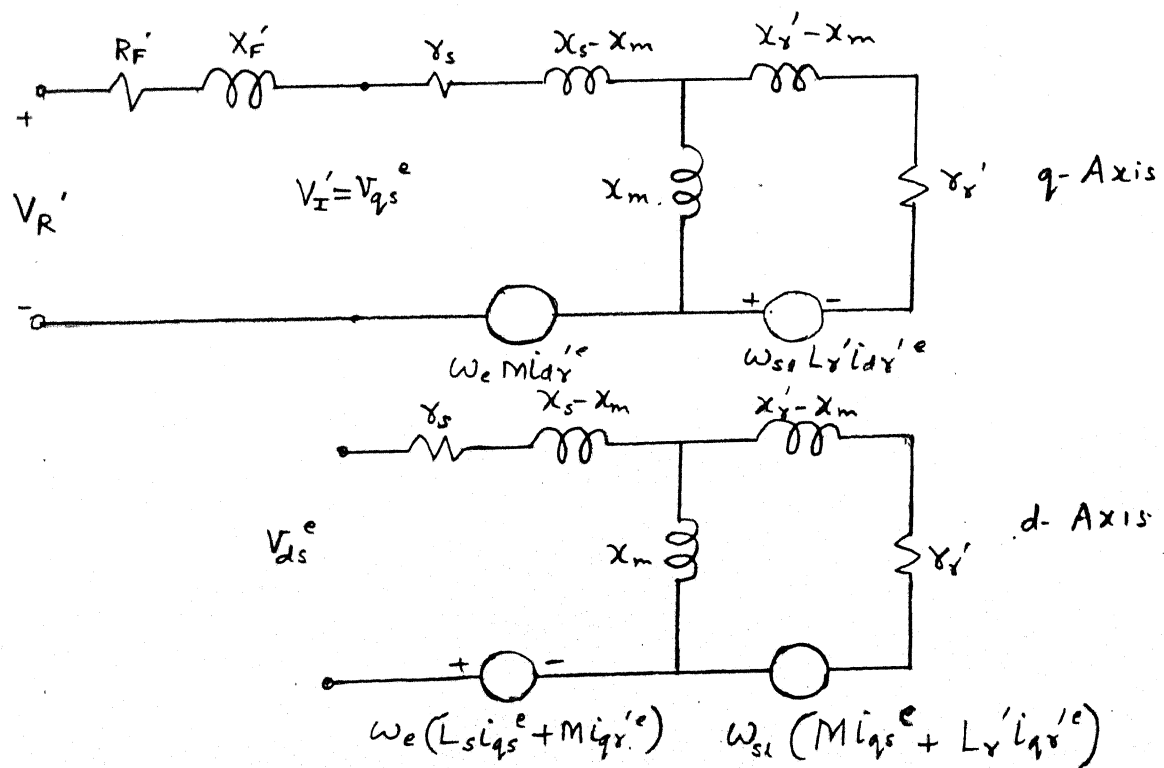


Fig. 3.7 Simplified d-q equivalent circuit

CHAPTER 4

ANALYSIS OF CONTROLLED CURRENT INDUCTION MOTOR DRIVE

4.1 INTRODUCTION:

In the previous chapter, we developed a complete model of the current source inverter fed induction motor. In this chapter steady state characteristics of the drive has been obtained and compared with voltage source inverter drive. Also a linearized model for open loop and closed loop operation around an operating point is developed. The linearized model is utilized for stability and transient response analysis of open and close loop drives with various controllers.

4.2 STEADY-STATE CHARACTERISTICS:

In steady state, in the synchronous reference frame, all currents and voltages will be constant/^{provided harmonics are neglected}. Thus all the derivatives or 'p' terms in Eqn. (3.32) are zero. Hence the steady-state machine equation is described as

$$\begin{bmatrix} v_{qs}^e \\ v_{ds}^e \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s & \omega_e L_s & 0 & \omega_e M \\ -\omega_e L_s & r_s & -\omega_e M & 0 \\ 0 & \omega_{sl} M & r_r' & \omega_{sl} L_r' \\ -\omega_{sl} M & 0 & -\omega_{sl} L_r' & r_r' \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ 0 \\ i_{qr}^e \\ i_{dr}^e \end{bmatrix} \quad (4.1)$$

Solving equations (3.43), (3.58) and (4.1) we get

$$T_e = 3 I_r^2 \frac{\omega_e M^2 s}{r_r [1 + (\frac{s \omega L_r'}{r_r'})^2]} \quad (4.2)$$

$$T_e = 3 \frac{1}{\omega_e} I_R^2 \frac{X_m^2 r_r' / s}{[(r_r' / s)^2 + (X_m + X_{lr}')^2]} \quad (4.3)$$

Equation (4.3) is the standard relationship for induction motor torque. The steady state equivalent circuit is shown in Fig.

4.1. From the equivalent circuit, we have

$$I_r'^2 = \frac{X_m^2}{(r_r' / s)^2 + (X_m + X_{lr}')^2} I_R^2 \quad (4.4)$$

$$T_e = \frac{3}{\omega_e} I_r'^2 \frac{r_r'}{s} \quad (4.5)$$

The steady-state slip-torque characteristics for a current controlled induction motor drive are shown in Fig. 4.2. The parameters for the induction motor used are given in Appendix III.

4.2.1 Comparison of Performance between current source and Voltage Source Drives:

In Table 4.1 various formulas which determine the motor characteristics are shown for the two types of drives: current source type and voltage source type. These formulas are derived from eqn. (4.1) and from corresponding equations applied

to the motor fed with voltage source inverter with 180° conduction. It is noted that the formulas for efficiency are the same for both types[5].

The resulting currents from eqn. (4.1) are used to compute the flux linkages [7] from eqn. (3.10). The results for the voltage source and the current source supplied motor are shown in Figs. 4.3 and 4.4. A comparison of the torque speed curves shows that the current source drive results in much less torque at low speeds but has a sharp peak closer to synchronous speed than the voltage source type. We also note that there is sharp rise in flux linkage as the slip approaches zero. This results in saturation and high losses in a practical machine. Thus operation at full current at low slip is to be avoided.

4.2.2 Linearized Model for Open Loop Operation:

One method available to study the transient performance of electric drives is perturbation analysis about an operating point. Small displacement theory has been very effective in studying stability [2,5]. This theory enables to establish linear equations which describe operation of a system for small changes about an operating point.

Each variable is considered to be composed of a steady - state and small-time varying component. For example:

$$i_{qs}^e = i_{qso}^e + \Delta i_{qs}^e \quad (4.6)$$

$$i_{dr}^e = i_{dro}^e + \Delta i_{dr}^e \quad (4.7)$$

$$i_{qr}^e = i_{qro}^e + \Delta i_{qr}^e \quad (4.8)$$

$$\omega_r = \omega_{ro} + \Delta \omega_r \quad (4.9)$$

$$V_R' = V_{Ro}' + \Delta V_R' \quad (4.10)$$

$$\omega_e = \omega_{eo} + \Delta \omega_e \quad (4.11)$$

$$T_L = T_{Lo} + \Delta T_L \quad (4.12)$$

These components are substituted into the original nonlinear equations (3.57) and (3.58). All purely steady-state terms drop out and all second-order perturbation terms are ignored. The resulting equations are linear in the perturbation variables which allows us to use linear control analytical techniques to synthesize the needed control.

The linearized equations in matrix form are

$$\begin{bmatrix} L & M & 0 & 0 \\ M & L_r' & 0 & 0 \\ 0 & 0 & L_r' & 0 \\ 0 & 0 & 0 & \frac{-2J}{P} \end{bmatrix} p \begin{bmatrix} \Delta i_{qs}^e \\ \Delta i_{qr}^e \\ \Delta i_{dr}^e \\ \Delta \omega_r \end{bmatrix} =$$

$$= - \begin{bmatrix} R & 0 & \omega_e M & 0 \\ 0 & r'_r & \omega_{slo} L'_r & -L'_r i'_{dro} \\ -\omega_{slo} M & -\omega_{slo} L'_r & r'_r & M i_{qso}^e + L'_r i'_{qro} \\ \frac{3P}{4} M i'_{dro} & 0 & \frac{3P}{4} M i_{qso}^e & 0 \end{bmatrix} \begin{bmatrix} \Delta i_{qs}^e \\ \Delta i_{qr}^e \\ \Delta i_{dr}^e \\ \Delta \omega_r \end{bmatrix} + \begin{bmatrix} -M i'_{dro} & 1 & 0 \\ -L'_r i'_{dro} & 0 & 0 \\ M i_{qso}^e + L'_r i'_{qro} & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta \omega_e \\ \Delta V'_R \\ \Delta T_L \end{bmatrix} \quad (4.13)$$

where,

$$L = L_F' + L_S \quad (4.14)$$

$$R = r_s + R_F' \quad (4.15)$$

If both sides of this matrix equation are premultiplied by the inverse of the coefficient matrix of the derivative vector, the resulting equations are arranged in state variable form.

$$p \begin{bmatrix} \Delta \underline{i} \\ \Delta \omega_r \end{bmatrix} = [A] \begin{bmatrix} \Delta \underline{i} \\ \Delta \omega_r \end{bmatrix} + [B] [\Delta \underline{u}] \quad (4.16)$$

where,

$$[B] = \begin{bmatrix} 0 & L'_r/L_L & 0 \\ -i'_{dro} & M/L_L & 0 \\ \frac{M i_{qso}^e + L'_r i'_{dro}}{L'_r} & 0 & 0 \\ 0 & 0 & -\frac{P}{2J} \end{bmatrix}$$

where,

$$\Delta \underline{i} = \begin{bmatrix} \Delta i_{qs}^e \\ \Delta i_{qr}^e \\ \Delta i_{dr}^e \end{bmatrix} ; [\Delta \underline{u}] = \begin{bmatrix} \Delta \omega_e \\ \Delta V_{R'} \\ \Delta T_L \end{bmatrix} \quad (4.17)$$

$$[A] = \begin{bmatrix} \frac{-L_r' R}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{-M L_r' i_{dro}^e}{L_1} \\ \frac{M R}{L_1} & -\frac{L_r'}{L_1} & \frac{L_r' L \omega_{ro} - \omega_e}{L_1} & \frac{L_r' L i_{dro}^e}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & \frac{-M i_{qso} - L_r' i_{qro}^e}{L_r'} \\ \frac{3}{8} \frac{p^2 M i_{dro}^e}{J} & 0 & \frac{3}{8} \frac{p^2 M i_{qso}^e}{J} & 0 \end{bmatrix} \quad (4.18)$$

$$L_1 = L L_r' - M^2 \quad (4.19)$$

4.2.3 Calculation of Transfer Function for Open Loop Drive:

In this study, the Levrier-Faddeev [27] method given in Appendix II is used to find the characteristic equation of the system of eqns. (4.16). The roots of the characteristic equation gives the poles or eigen values of the system.

To define a complete transfer function it is also necessary to determine the zeros. These are unique to the

choice of input and output while the poles are characteristics of the system. One method of obtaining the zeroes involves transformation of the system equations to the phase variable form. Such a transformation is done using a recursive algorithm described by Tuel [15] and Rane [16] and is given in Appendix II. The algorithm provides a polynomial equation whose roots are the zeroes of the transfer function. Thus, for a particular operating point and a particular choice of input and output, the complete transfer function is found.

4.2.4 Stability Analysis of Open Loop Drive:

Only a small portion of the slip-torque characteristics is shown in Fig. 4.2. Examination of the characteristics indicates two regions of operation - one with positive slope and the other with negative slope. The negative sloped portions are well known to be inherently unstable. This type of instability will be referred to as a static instability. It is also possible to have dynamic instability on either portion of the characteristics. This is caused by negative electrical damping which is highly dependent on the selection of operating point and machine parameters.

For controlled current inverter operation, the steady - state operating point can occur on either the upper or lower portion of the characteristic. For example, if operation is constrained such that the machine is never driven into a highly saturated condition, operation would be at point A.

Operation at point B, which yields the same output torque, corresponds to a highly saturated condition. For low torque and rated flux conditions, the steady-state operating point would be on the upper portion of a low current magnitude characteristic, for example, at point C which is on the statically stable side of the $I_R = 40A$ characteristic.

The open loop system shown in Fig. 4.5 is described by equation (4.16) for small disturbances about a steady-state point. For a specific input two of the three elements of $[\Delta u]$ are set equal to zero. The transfer function is obtained in factored form. Stability and transient response are immediately apparent from the pole-zero locations.

If open-loop operation is attempted by applying an uncontrolled rectifier voltage and by commanding a constant inverter switching frequency (no current or slip control), the drive will be unstable. We examine the transfer function $\Delta I_R' / \Delta V_R'$. The transfer function for open-loop operation corresponding to four different points are given in Table 4.2.

It is seen from the Table 4.2 that the system is dynamically unstable at all four operating points. This type of instability results in one right-half plane pole in the linearized transfer function. In addition, for unsaturated conditions with sizable torque output, the system is also statically unstable which results in a second pole in the

right-half plane at point A. Therefore closed-loop control is imperative for stable operation.

4.3 CLOSED-LOOP CONTROL ANALYSIS:

On examining equation (4.17) we see that two control variables are available for system stabilization. These system inputs are the rectifier voltage and the frequency command to the inverter. We will now study the improvement in stability provided by the particular feedback.

4.3.1 Slip Frequency Control:

With slip frequency control, incremental changes in rotor speed are related to incremental changes in electrical frequency by the constraint

$$\Delta\omega_e = \Delta\omega_r + \Delta\omega_{sl} \quad (4.20)$$

Slip frequency control forces electrical frequency to change in response to rotor speed, which tends to maintain a constant angular displacement between rotor and stator MMF's during both steady-state and transient conditions.

The system for slip frequency control is described by

$$p[\Delta x] = [A] [\Delta x] + [B] [\Delta u] \quad (4.21)$$

where,

$$[\Delta x]^t = [\Delta i_{qs}^e \quad \Delta i_{qr}^e \quad \Delta i_{dr}^e \quad \Delta\omega_r] \quad (4.22)$$

$$[\Delta u]^t = [\Delta \omega_{sl} \quad \Delta V_R' \quad \Delta T_L] \quad (4.23)$$

$$[A] = \begin{bmatrix} \frac{-L_r' R}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{-L_r' M i_{dro}'^e}{L_1} \\ \frac{M R}{L_1} & \frac{-L r_r'}{L_1} & \frac{L_r' L \omega_{ro} - \omega_e}{L_1} & \frac{M^2 i_{dro}'^e}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & 0 \\ \frac{3}{8} \frac{p^2 M i_{dro}'^e}{J} & 0 & \frac{3}{8} \frac{p^2 M i_{qso}'^e}{J} & 0 \end{bmatrix} \quad (4.24)$$

The matrix [B] remains unaffected.

If the closed-loop operation is attempted by applying an uncontrolled rectifier voltage and by controlling the inverter switching frequency (no current control but slip control), the drive is stable in positive slope portion only and unstable in negative slope portion. This is seen by calculating the transfer functions $\Delta I_R' / \Delta V_R'$ or $\frac{\Delta \omega_r}{\Delta \omega_{sl}}$. The transfer functions for slip control corresponding to four different points are given in Table 4.4 and Table 4.5.

We see from the table 4.4 that the system is dynamically as well as statically stable in positive sloped region because all the eigen-values of the system are lying in the left-half plane at point A and C. The system is dynamically as well as statically unstable in negative sloped region because of two eigen values of the system at B and D are lying in the right-half

plane. Thus we see that there is improvement in stability with slip control compare to uncontrolled open loop operation. Although this type of control has a stabilizing effect, it is not capable of ensuring stable operation under all operating conditions.

4.3.2 Independent Current and Slip Frequency Control using Proportional Controller:

To obtain steady-state current control along with improved system transient response, the rectifier voltage must be constrained to respond to the error between a commanded value and the actual value of the dc link current. A proportional controller is used for this purpose. The rectifier voltage can then be expressed as

$$\Delta V_R' = K_1 (\Delta I_R'^* - \Delta I_R') \quad (4.25)$$

The system matrix equation including the slip frequency and current magnitude control using proportional controller shown in Fig. 4.6 is

$$p[\Delta x] = [A] [\Delta x] + [B] [\Delta u] \quad (4.26)$$

where,

$$[\Delta u]^t = [\Delta \omega_{sl} \quad \Delta I_R'^* \quad \Delta T_L] \quad (4.27)$$

$$[A] = \begin{bmatrix} \frac{-L_r' R'}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{-L_r' M i_{dro}^e}{L_1} \\ \frac{M R'}{L_1} & \frac{-L_r r_r'}{L_1} & \frac{L_r' L \omega_{ro} - \omega_e}{L_1} & \frac{M^2 i_{dro}^e}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & 0 \\ \frac{3}{8} \frac{P^2 M i_{dro}^e}{J} & 0 & \frac{3}{8} \frac{P^2 M i_{qso}^e}{J} & 0 \end{bmatrix} \quad (4.28)$$

$$[B] = \begin{bmatrix} 0 & \frac{K_1 L_r'}{L_1} & 0 \\ -i_{dro}^e & \frac{-K_1 M}{L_1} & 0 \\ \frac{(M i_{qso}^e + L_r' i_{dro}^e)}{L_r'} & 0 & 0 \\ 0 & 0 & \frac{-P}{2J} \end{bmatrix} \quad (4.29)$$

where $R' = R + K_1$

And for frequency control the matrix A becomes

regulator. Hence,

$$\Delta I_R^* = K_2 (\Delta \omega_r^* - \Delta \omega_r) \quad (4.31)$$

Using equations (4.25) and (4.31), we get the matrix equation for the system shown in Fig. 4.7 as

$$p[\Delta x] = [A] [\Delta x] + [B] [\Delta u] \quad (4.32)$$

where

$$[A] = \begin{bmatrix} \frac{-L_r' R'}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{-(K_1 L_r' + M L_r' i_{dro}^e)}{L_1} \\ \frac{M R'}{L_1} & \frac{-L_r'}{L_1} & \frac{L_r' L_{ro} \omega_e}{L_1} & \frac{(K_1 M + L_r' i_{dro}^e)}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & \frac{-(M i_{qso}^e + L_r' i_{gro}^e)}{L_r'} \\ \frac{3}{8} \frac{p^2 M i_{dro}^e}{J} & 0 & \frac{3}{8} \frac{p^2 M i_{qso}^e}{J} & 0 \end{bmatrix} \quad (4.33)$$

$$[B] = \begin{bmatrix} 0 & \frac{K_1 K_2 L_r'}{L_1} & 0 \\ -i_{dro}^e & \frac{-K_1 K_2 M}{L_1} & 0 \\ \frac{(M i_{qso}^e + L_r' i_{gro}^e)}{L_r'} & 0 & \frac{-p}{2J} \end{bmatrix} \quad (4.34)$$

$$[\Delta u]^t = [\Delta \omega_e \quad \Delta \omega_r^* \quad \Delta T_1] \quad (4.35)$$

The transfer function for independent speed and slip frequency control is obtained by replacing ω_e by ω_{sl} in the independent variable vector $[u]$. Also the column of matrix A associated with ω_r is changed to correspond to $\omega_{sl} = \omega_s - \omega_r$. Thus the matrix A is

$$[A] = \begin{bmatrix} \frac{-L_r' R'}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{-(K_1 L_r' + M L_r' i_{dro}^e)}{L_1} \\ \frac{M R'}{L_1} & \frac{-L_r'}{L_1} & \frac{L_r' L \omega_{ro} - \omega_e}{L_1} & \frac{(K_1 M + M^2 i_{dro}^e)}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & 0 \\ \frac{3}{8} \frac{P^2 M i_{dro}^e}{J} & 0 & \frac{3}{8} \frac{P^2 M i_{qso}^e}{J} & 0 \end{bmatrix} \quad (4.36)$$

The transfer functions $\Delta \omega_r / \Delta \omega_r^*$, $\frac{\Delta \omega_r}{\Delta \omega_e}$ and $\frac{\Delta \omega_r}{\Delta \omega_{sl}}$ have been calculated and are shown in Tables 4.10, 4.11 4.12 and 4.13.

We observe that the system is dynamically as well as statically stable under all operating conditions as all the eigen-values of the system lie in the left-half plane for all the four points.

By looking at the location of the poles of the system we see that it is relatively more stable than independent current and slip frequency control.

4.3.4 Independent Speed and Slip Frequency Control using Proportional Plus Integral Controller:

We now use an integral plus proportional controller to give satisfactory speed of response with zero steady-state error. The current magnitude is set by the error between the reference speed and actual speed through a proportional plus integral controller. Hence,

$$\Delta I_R^* = \frac{K_2(1+p\tau)}{p} (\Delta \omega_r^* - \Delta \omega_r) \quad (4.37)$$

To include the compensator in the analysis, a fifth state variable ΔQ is defined. ΔQ is defined to be the output of the integral controller, that is

$$\Delta Q = \frac{K_2}{p} (\Delta \omega_r^* - \Delta \omega_r) \quad (4.38)$$

The reference current can then be expressed as

$$\Delta I_R^* = \Delta Q (1 + \tau p) \quad (4.39)$$

Using equations (4.25), (4.37) and (4.38) we get the system matrix equation for integral plus proportional controller shown in Fig. 4.8 in the state space form as

$$p[\Delta x] = [A][\Delta x] + [B][\Delta u] \quad (4.40)$$

where,

$$[A] = \begin{bmatrix} \frac{-L_r' R'}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{K_1 L_r'}{L_1} & \frac{-(K_1 K_2 \tau L_r' + M L_r' i_{dro}^e)}{L_1} \\ \frac{M R'}{L_1} & \frac{-L r_r'}{L_1} & \frac{L_r' L \omega_{ro} - \omega_e}{L_1} & \frac{-K_1 M}{L_1} & \frac{(K_1 K_2 \tau M + L L_r' i_{dro}^e)}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & 0 & \frac{-(M i_{qso}^e + L_r' i_{qro}^e)}{L_r'} \\ 0 & 0 & 0 & 0 & -K_2 \\ \frac{3}{8} \frac{p^2 M i_{dro}^e}{J} & 0 & \frac{3}{8} \frac{p^2 M i_{qso}^e}{J} & 0 & 0 \end{bmatrix} \quad (4.41)$$

$$[B] = \begin{bmatrix} 0 & \frac{K_1 K_2 \tau L_r'}{L_1} & 0 \\ -i_{dro}^e & \frac{-K_1 K_2 \tau M}{L_1} & 0 \\ \frac{(M i_{qso}^e + L_r' i_{qro}^e)}{L_r'} & 0 & 0 \\ 0 & K_2 & 0 \\ 0 & 0 & \frac{-P}{2J} \end{bmatrix} \quad (4.42)$$

$$[\Delta x]^t = [\Delta i_{qs}^e \quad \Delta i_{qr}^e \quad \Delta i_{dr}^e \quad \Delta Q \quad \Delta \omega_r] \quad (4.43)$$

The transfer function for independent speed and slip frequency control with PI controller is obtained by replacing ω_e by equation (4.20). Thus the matrix A for the system is

$$[A] = \begin{bmatrix} \frac{-L_r' R'}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{K_1 L_r'}{L_1} & \frac{-(K_1 K_2 \tau L_r' + M L_r' i_{dro}^e)}{L_1} \\ \frac{M R'}{L_1} & \frac{-L_r' R'}{L_1} & \frac{L_r' L \omega_{ro} - \omega_e}{L_1} & \frac{-K_1 M}{L_1} & \frac{(K_1 K_2 \tau M + M^2 i_{dro}^e)}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r}{L_r'} & 0 & 0 \\ 0 & 0 & 0 & 0 & -K_2 \\ \frac{3}{8} \frac{p^2 M i_{dro}^e}{J} & 0 & \frac{3}{8} \frac{p^2 M i_{qso}^e}{J} & 0 & 0 \end{bmatrix} \quad (4.44)$$

The transfer function $\Delta \omega_r / \Delta \omega_r^*$, $\Delta \omega_r / \Delta \omega_e$ and $\Delta \omega_r / \Delta \omega_{sl}$ for four different operating points are shown in Tables 4.14, 4.15, 4.16 and 4.17.

We see that all the poles are lying in the left half plane so that system is stable under all operating conditions.

4.4 EFFECT OF CONTROLLER GAIN ON STABILITY:

The location of poles and zeroes depend on the operating point as shown in Table 4.2. When the controller gain is increased, the system may or may not be stable for all values of gain. The root locus for the transfer function $\Delta I_R' / \Delta I_R'^*$ corresponding to point A is shown in Fig. 4.9. As the gain is increased, the pole in the right half plane moves towards left-half plane and crosses the imaginary axis at $K_1 = 1.25$. So we see that though the open-loop system is unstable but the close loop system is stable for the values of gain greater than 1.25 corresponding to point A.

The Fig. 4.10 shows the root locus for the transfer function $\Delta I_R' / \Delta I_R'^*$ corresponding to point B. As the gain is increased the system becomes stable at K_1 equal to 1.2 because all the poles lie in the left-half plane. It becomes unstable beyond K_1 equal to 1.4 because one pole always lies in the right half plane.

The root locus for the transfer function $\Delta \omega_r / \Delta \omega_r^*$ with proportional plus integral is shown in Figs. 4.11 and 4.12. Corresponding to, point A and B we see that the system is stable for all values of gain. For large values of gain the system corresponding to point A is more damped than corresponding to point B.

For a particular of gain the system may or may not be stable various operating points along the steady state curve. So adaptive controller may be used for operating in the whole range of torque-slip characteristic.

4.5 COMPARISON OF TRANSIENT RESPONSE FOR VARIOUS CONTROL METHODS:

The Table 4.18 shows the rise time, delay time, percentage peak overshoot and setting time of different controls methods. It can be seen that open loop transient response is fast but the percentage peak overshoot is high and system is very under-damped. With the help of proportional controller the system can be made over-damped or critically damped by varying controller gain. The transient response corresponding to transfer function $\Delta \omega_r / \Delta \omega_r^*$ with proportional plus integral controller has smaller percentage peak overshoot compared to open loop operation and its rise time is lower than the transfer function corresponding to $\Delta I_R / \Delta I_R^*$.

TABLE 4.1

COMPARISON OF PERFORMANCE FORMULA BETWEEN CURRENT
SOURCE AND VOLTAGE SOURCE DRIVES

	Current source type	Voltage source type
Torque	$3 \frac{S^2 \omega_e^2 M^2 r_r' I_R^2}{r_r'^2 + S^2 \omega_e^2 L_r'^2}$	$\frac{\pi^2}{18} \cdot \frac{S \omega_e^2 M^2 r_r'}{(r_s r_r' - S \omega_e^2 L_s L_r \sigma)^2 + \omega_e^2 (r_r' L_s + S r_s L_r')^2}$

Efficiency (η)**	$\frac{S(1-S) \omega_e^2 M^2 r_r'}{r_s (r_r'^2 + S^2 \omega_e^2 L_r'^2) + S \omega_e^2 M^2 r_r'}$
-------------------------	---

** $\eta = \frac{\text{Mechanical output}}{\text{Input}}$
(Iron loss neglected)

where $\sigma = 1 - \frac{M^2}{L_s L_r'}$

TABLE 4.2

OPEN LOOP TRANSFER FUNCTION $\Delta I_R' / \Delta V_R'$ FOR UNCONTROLLED
OPERATION AT $f_c = 50$ Hz.

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	$-1.46 \pm j31.79$ -2.21	$-28.55 \pm j50.41$ 37.42 -2.31
B	0.02	60	62.27	$-6.11 \pm j16.1$ 7.1	$-22 \pm j26.9$ $11 \pm j11.1$
C	0.002	40	18.31	$-1.36 \pm j21.9$ -2.4	$-21.99 \pm j33.9$ 24.55 -2.56
D	0.033	40	18.44	$-5.39 \pm j13.2$ 5.7	$5.8 \pm j18.7$ -20.5 -13.2

TABLE 4.3

OPEN LOOP TRANSFER FUNCTION $\Delta \omega_r / \Delta \omega_e$ FOR UNCONTROLLED
OPERATION AT $f_e = 50$ Hz.

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-2.23 -1.18	-28.6 + j50.4 37.42 -2.3
B	0.02	60	62.27	12.52 -1.3	-22.4 + j26.9 11 + j11.1
C	0.002	40	18.31	-2.4 -0.38	-21.99 + j33.9 24.5 -2.56
D	0.033	40	18.44	37.9 -0.4	5.8 + j18.7 -20.5 -13.2

TABLE 4.4

TRANSFER FUNCTION $\Delta I_R' / \Delta V_R'$ FOR SLIP FREQUENCY
CONTROL at $f_e = 50$ Hz.

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	$-2.56 \pm j0.94$	$-3.59 \pm j10.7$ -13.3 -1.48
B	0.02	60	62.27	$-2.56 \pm j6.3$	$1.6 \pm j18.7$ -23.02 -2.24
C	0.002	40	18.31	$-2.56 \pm j0.63$	-18.2 $-1.62 \pm j6.8$ -0.57
D	0.033	40	18.44	$-2.56 \pm j10.37$	$4 \pm j4.9$ -29.3 -0.7

TABLE 4.5

TRANSFER FUNCTION $\Delta \omega_r / \Delta \omega_{sl}$ FOR SLIP FREQUENCY
CONTROL AT $f_e = 50$ Hz.

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	125.62 -2.29	$-3.59 \pm j10.69$ -13.3 -1.48
B	0.02	60	62.27	137.34 12.3	$1.63 \pm j18.66$ -23.02 -2.24
C	0.002	40	18.31	84.91 -2.52	-18.18 $-1.62 \pm j6.98$ -0.57
D	0.003	40	18.44	88.75 36.15	$4.01 \pm j20.86$ -29.34 -0.67

TABLE 4.6

TRANSFER FUNCTION $\Delta I_R' / \Delta I_R^*$ WITH INDEPENDENT CURRENT
AND INPUT FREQUENCY CONTROL AT $f_e = 50$ Hz.

Point V	Slip	I_R (A)	K_1	T_e (N-m)	Zeroes	Poles
A	0.003	60	1.3	57.7	-1.46 + j31.8 -2.21	-143.1 -6.03 + j7.04 -0.91
B	0.02	60	1.3	62.27	-6.1 + j16.1 7.1	-148.8 -3.06 + j8.1 -1.2
C	0.002	40	1.3	18.31	-1.3 + j21.9 -2.41	-148.6 -2.7 + j12.6 -2.14
D	0.033	4.0	0.8	18.44	-5.4 + j13.2 5.66	-99.8 -2.16 + j14.45 -0.36

TABLE 4.7

TRANSFER FUNCTION $\Delta \omega_r / \Delta \omega_e$ FOR INDEPENDENT CURRENT AND
INPUT FREQUENCY CONTROL AT $f_e = 50$ Hz.

Point	Slip	I_R (A)	K_1	T_{e-m}	Zeroes	Poles
A	0.003	60	1.3	57.7	-9.92 -0.86	-143.1 -6.03 + j7.04 -0.91
B	0.02	60	1.3	62.27	17.3 -1.71	-148.8 -3.06 + j8.1 -1.2
C	0.002	40	1.3	18.31	-49.51 -2.2	-148.6 -2.7 + j12.6 -2.14
D	0.033	40	0.8	18.44	43.34 -0.96	-99.8 -2.16 + j14.45 -0.36

TABLE 4.8

TRANSFER FUNCTION $\Delta I_R' / \Delta I_R'^*$ WITH INDEPENDENT CURRENT
AND SLIP FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER
AT $f_e = 50$ Hz.

Point	Slip	I_R (A)	K_1	T_e (N-m)	Zeroes	Poles
A	0.003	60	1.3	57.7	$-2.56 \pm j0.94$ -0.0001	-149.9 $-2.48 \pm j2.8$ -1.2
B	0.02	60	1.3	62.27	$-2.56 \pm j6.28$	-150.0 $-2.37 \pm j9.3$ -1.3
C	0.002	40	1.3	18.31	$-2.56 \pm j0.63$ -0.0001	-150.8 $-2.48 \pm j2.24$ -0.31
D	0.033	40	0.8	18.44	$-2.56 \pm j10.37$	-100.26 $-1.9 \pm j14.88$ -0.39

TABLE 4.9

TRANSFER FUNCTION $\Delta \omega_r / \Delta \omega_{sl}$ FOR INDEPENDENT CURRENT
AND SLIP FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER
AT $f_c = 50$ Hz.

Point	Slip	I_R (A)	K_1	T_e (N-m)	Zeroes	Poles
A	0.003	60	1.3	57.5	-9.92 -0.86	-149.95 -2.5 ± j2.84 -1.18
B	0.02	60	1.3	62.27	17.27 -1.7	-150.03 -2.37 ± j9.3 -1.31
C	0.002	40	1.3	18.31	-49.5 -2.2	-150.8 -2.5 ± j2.24 -0.32
D	0.033	40	0.8		43.34 -0.96	-100.26 -1.9 ± j4.9 -0.39

TABLE 4.10

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_r^*$ FOR INDEPENDENT CURRENT AND
FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER

$$f = 50 \text{ Hz}, \quad K_1 = 1.3, \quad K_2 = 1$$

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	$-2.56 \pm j2.9$	-137.3 -1.6 $-8.6 \pm j5.2$
B	0.02	60	62.27	$-2.56 \pm j9.25$	-142.9 $-2.27 \pm j8.2$ -8.56
C	0.002	40	18.31	$-2.56 \pm j2.7$	-146.1 $-3.86 \pm j12.7$ -2.25
D	0.033	40	18.44	$-2.56 \pm j14.88$	-148.67 $-3.2 \pm j13.75$ -1.03

TABLE 4.11

TRANSFER FUNCTION $\Delta \omega_r / \Delta \omega_e$ FOR INDEPENDENT CURRENT AND
FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER

$$f = 50 \text{ Hz}, K_1 = 1.3, K_2 = 1$$

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-6.5	-137.3
				-2.2	$-8.6 \pm j5.2$
					-1.6
B	0.02	60	62.27	12.61	-143.0
				-6.7	$-2.27 \pm j8.18$
					-8.56
C	0.002	40	18.31	-3.92	-146.1
				-2.4	$-3.9 \pm j12.7$
					-2.55
D	0.33	40	18.44	38.05	-148.67
				-4.05	$-3.1 \pm j13.75$
					-1.03

TABLE 4.12

TRANSFER FUNCTION $\Delta\omega_r / \Delta\omega_r^*$ FOR INDEPENDENT CURRENT AND
SLIP FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER

$$f = 50 \text{ Hz}, K_1 = 1.3, K_2 = 1$$

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	$-2.56 \pm j2.9$	-144.7 $-2.52 \pm j2.94$ -6.36
B	0.02	60	62.27	$-2.56 \pm j9.24$	-144.35 $-2.44 \pm j9.39$ -6.86
C	0.002	40	18.31	$-2.56 \pm j2.7$	-148.4 $-2.08 \pm j2.48$ -3.59
D	0.033	40	18.44	$-2.56 \pm j14.9$	-148.8 $-1.9 \pm j13.6$ -3.26

TABLE 4.13

TRANSFER FUNCTION $\Delta\omega_r / \Delta\omega_{sl}$ FOR INDEPENDENT CURRENT AND
SLIP FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER

$$f = 50 \text{ Hz}, K_1 = 1.3, K_2 = 1$$

Points	Slip	I_B (A)	T (N-m)	Zeroes	Poles
A	0.003	60	57.7	-9.92 -0.86	-144.7 -2.52±j2.94 -6.36
B	0.02	60	62.27	17.27 -1.71	-144.4 -2.44±j9.4 -6.86
C	0.002	40	18.31	-49.51 -2.2	-148.4 -2.06±j2.48 -3.59
D	0.033	40	18.44	-50.36 41.16	-148.85 -1.99±j13.6 -3.26

TABLE 4.14

TRANSFER FUNCTION $\Delta\omega_r / \Delta\omega_r^*$ WITH INDEPENDENT CURRENT AND
FREQUENCY CONTROL USING PI CONTROLLER

Frequency = 50 Hz, $K_1 = 1.3$, $K_2 = 1.0$, $\tau = 0.1$

Points	Slip	I_R (A)	Zeroes	Poles
A	0.003	60	-10.0 $-2.56 \pm j2.9$	-142.6 $-6.2 \pm j7.2$ $-0.57 \pm j7.74$
B	0.02	60	$-2.56 \pm j9.25$ -10.0	-148.25 $-3.1 \pm j7.97$ $-0.84 \pm j2.5$
C	0.002	40	-10.0 $2.56 \pm j2.71$	-148.37 $-2.8 \pm j2.7$ -2.1 -0.09
D	0.033	40	$-2.56 \pm j14.9$ -10.0	-150.9 $-3.3 \pm j13.9$ $0.73 \pm j1.46$

TABLE 4.15

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_e$ WITH INDEPENDENT CURRENT AND
INPUT FREQUENCY CONTROL USING PI CONTROLLER

Frequency = 50 Hz, $K_1 = 1.3$, $K_2 = 1.0$, $\tau = 0.1$

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-9.92 -0.86 -0.0012	-142.6 -6.2 ± j7.2 -0.57 ± j.75
B	0.02	60	62.27	17.3 -1.71	-148.25 -3.1 ± j7.97 -0.84 ± j2.5
C	0.002	40	18.31	-49.5 -2.2 -0.001	-148.4 -2.8 ± j12.7 -2.1 -0.09
D	0.033	40	18.44	-50.36 41.16	-150.9 -3.3 ± j13.9 0.7 ± j1.5

TABLE 4.16

TRANSFER FUNCTION $\Delta \omega_r / \Delta \omega_r^*$ WITH INDEPENDENT CURRENT AND
SLIP FREQUENCY CONTROL USING PI CONTROLLER

Frequency = 50 Hz, $K_1 = 1.3$, $K_2 = 1.0$, $\tau = 0.1$

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-10 -2.56±j2.9	-149.5 -2.5±j2.8 -0.8±j2.2
B	0.02	60	62.27	-2.56±j9.25 -10	-149.5 -2.36±j9.3 -0.9±j2.1
C	0.002	40	18.31	-10.0 -2.56±j2.7	-150.6 -2.57±j2.23 -0.18±j1.7
D	0.033	40	18.44	-2.56±j14.9 -10	-151 -2.23±j13.3 -0.29±j1.68

TABLE 4.17

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_{sl}$ WITH INDEPENDENT CURRENT AND
SLIP FREQUENCY CONTROL USING PI CONTROLLER

Frequency = 50 Hz, $K_1 = 1.3$, $K_2 = 1.0$, $\tau = 0.1$

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-9.92	-149.5
				-0.86	$-2.48 \pm j2.8$
				-0.0013	$-0.82 \pm j2.17$
B	0.02	60	62.27	17.3	-149.5
				-1.71	$-2.4 \pm j9.3$
					$-0.9 \pm j2.14$
C	0.002	40	18.31	-49.51	-150.6
				-2.2	$-2.58 \pm j2.23$
				-0.0001	$-0.18 \pm j1.7$
D	0.033	40	18.44	-50.36	-151.0
				41.2	$-2.23 \pm j13.5$
					$-0.3 \pm j1.7$

TABLE 4.18

COMPARISON OF TRANSIENT RESPONSE FOR VARIOUS CONTROL METHODS

$$K_1 = 1.3, K_2 = 1, \tau = 0.1$$

Transfer Function	Point	Rise time (sec)	Delay time (sec)	% peak overshoot	Setting time (sec)
$\Delta I_R' / \Delta V_R'$	A	0.091	0.06	85%	1.1
$\Delta I_R' / \Delta V_R'$	A	2.3	0.45	Overdamped	4.8
	B	2.6	0.8	Overdamped	4.7
$\Delta I_R' / \Delta I_R^{**}$	B	1.7	0.68	Overdamped	3.3
$\Delta \omega_r / \Delta \omega_r^*$	A	1.15	0.62	2.5%	2.4
with speed regulator	B	2.5	1.5	Overdamped	3.0
$\Delta \omega_r / \Delta \omega_r^*$	A	0.95	0.4	31%	6.0
with PI controller	B	0.9	0.5	28%	5.7

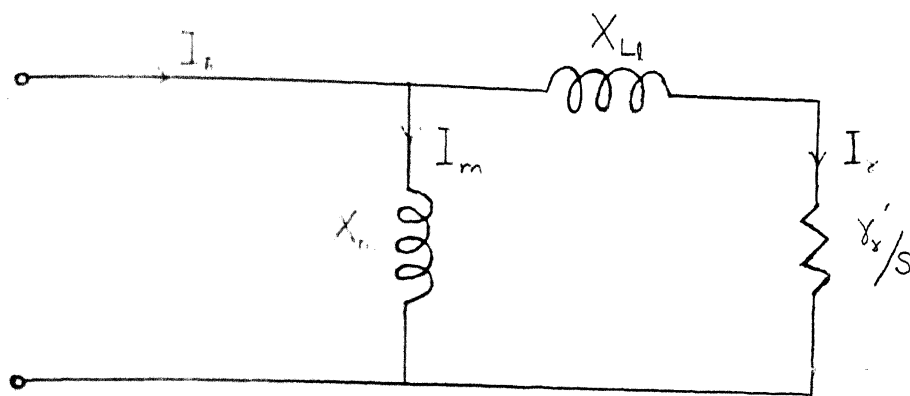


Fig. 4.1 Steady state equivalent circuit of CSI fed Induction motor.

TORQUE – SLIP CURVE

CURRENT = 60 & 40 AMP., FREQ.=50 HZ.

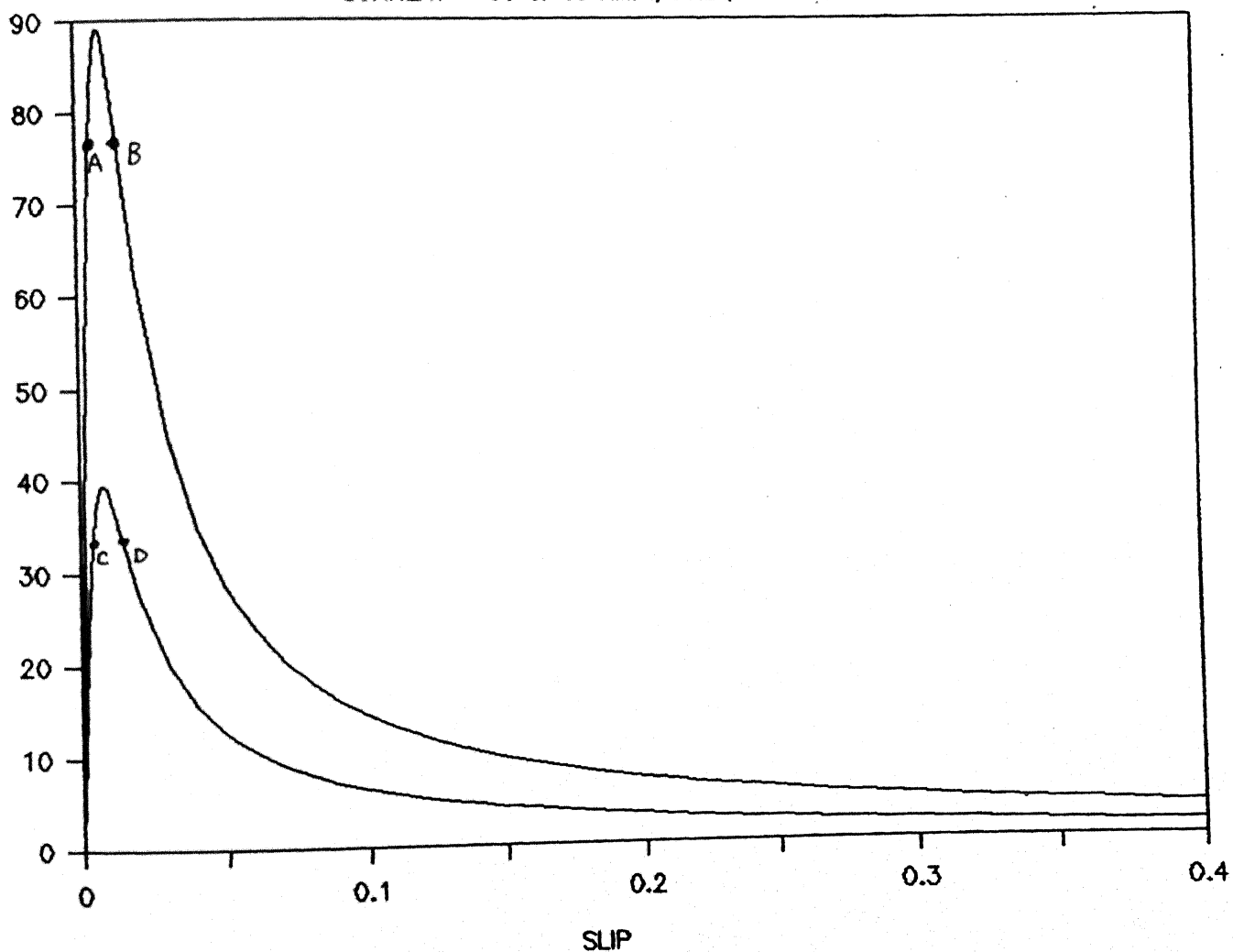


Fig. 4.2 Steady-state controlled curve induction motor characteristics.

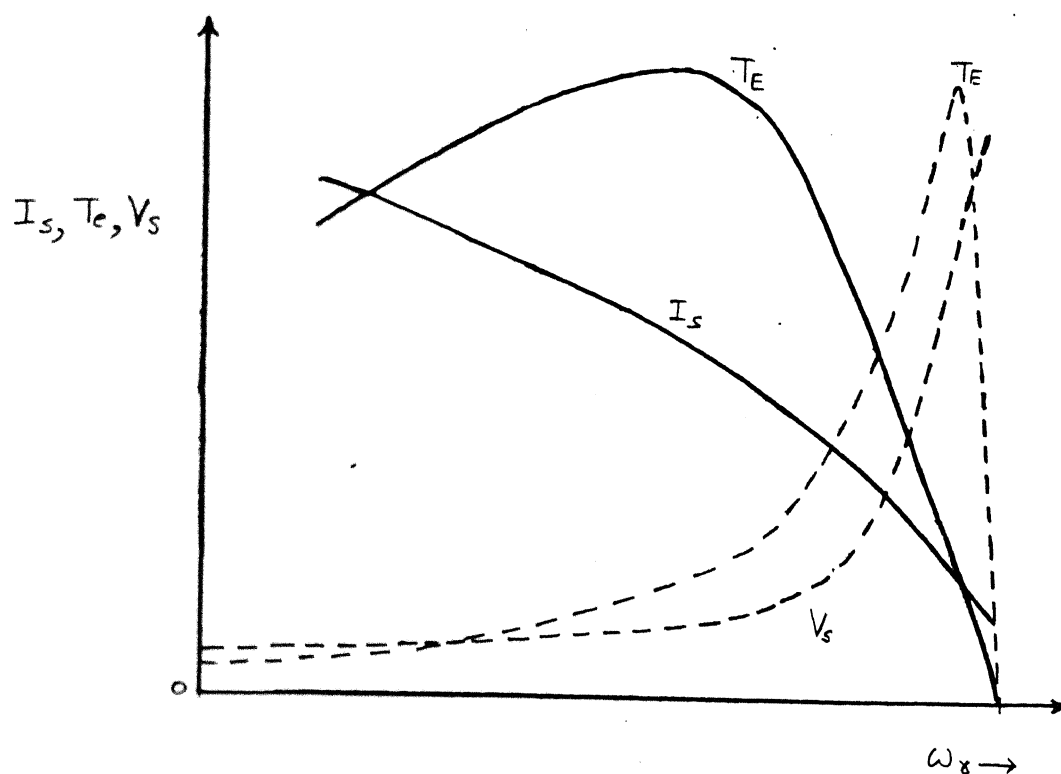


Fig. 4.3 Developed torque and stator voltage and current characteristics.

--- For CSI — For VSI

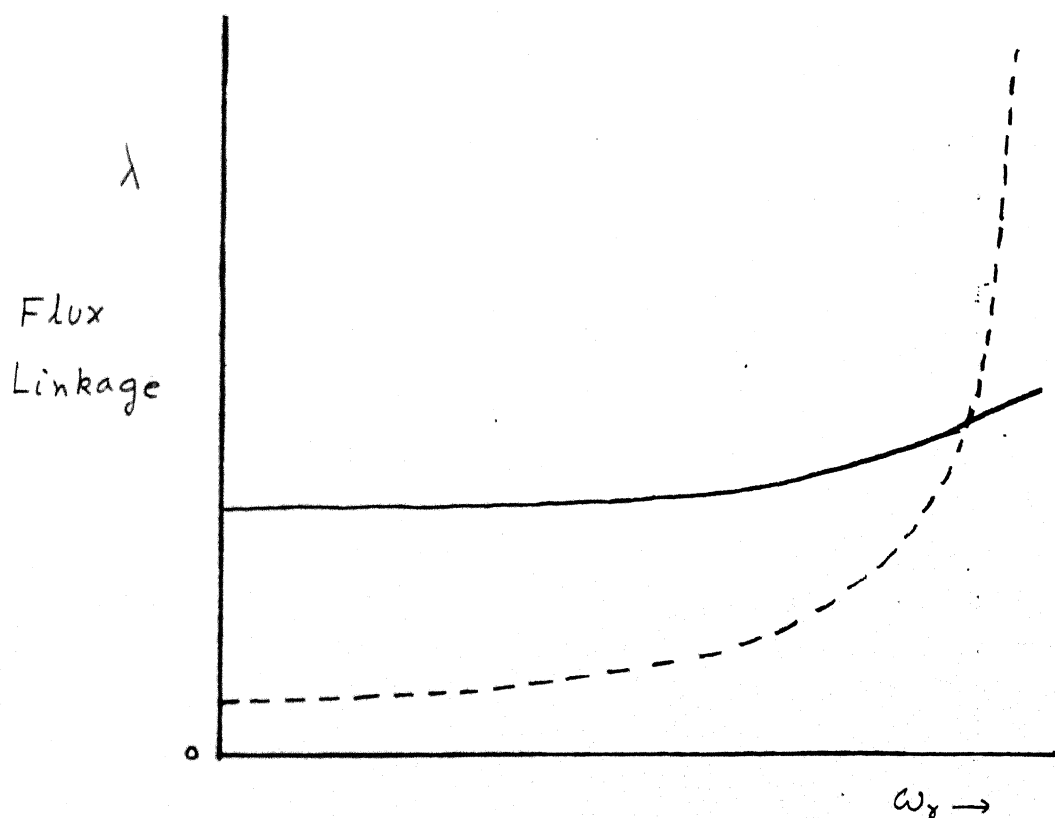


Fig. 4.4 Flux linkage characteristics

--- For CSI — For VSI

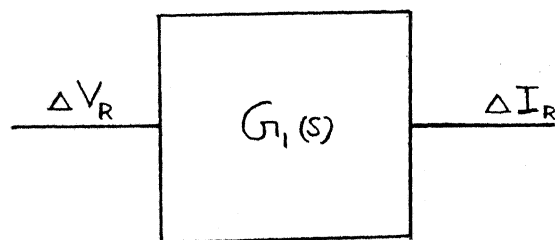
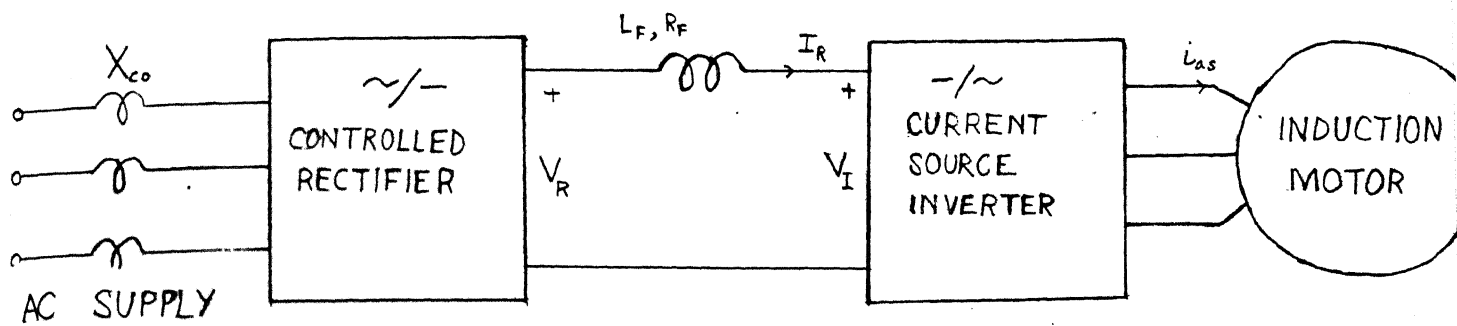


Fig. 4.5 Open Loop System

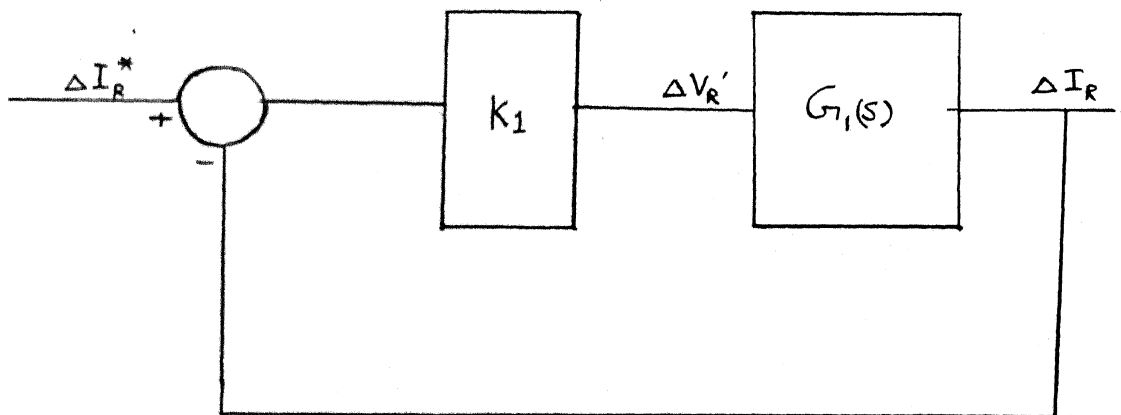
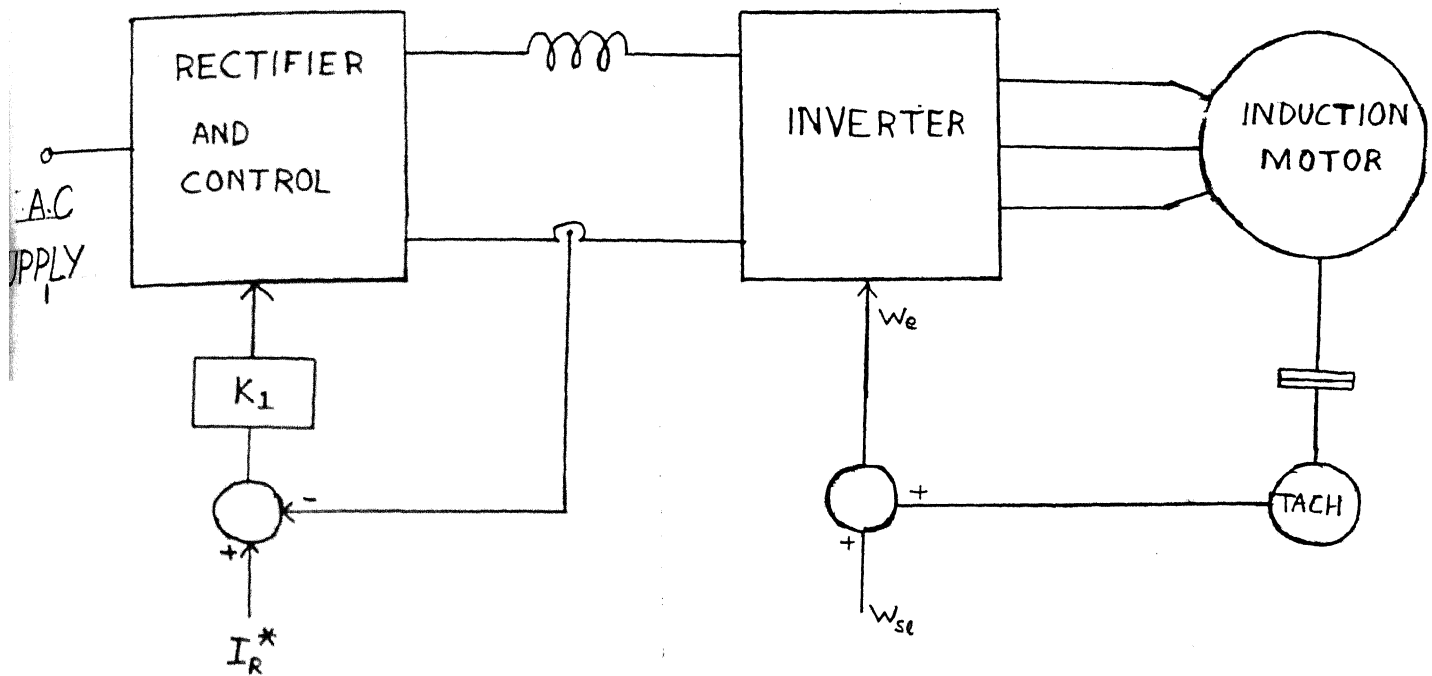


Fig. 4.6 Independent current and slip frequency control using proportional controller.

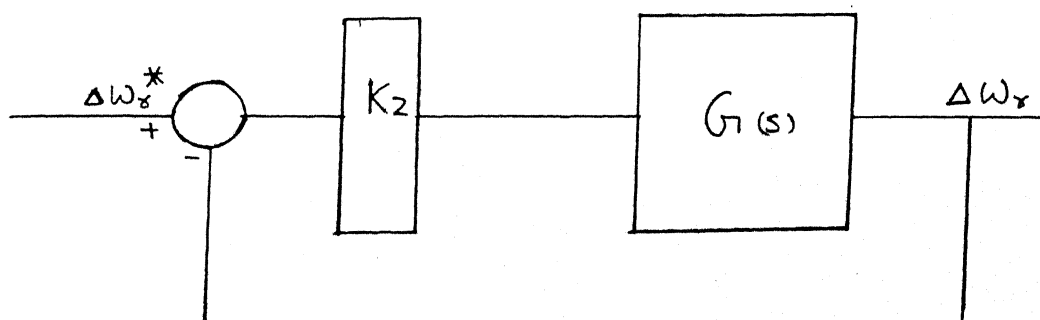
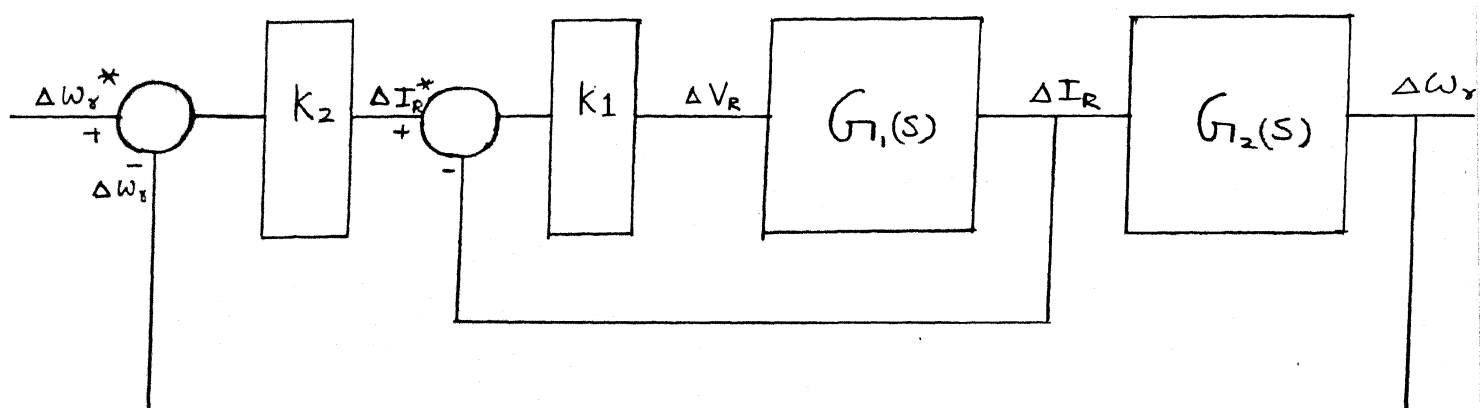
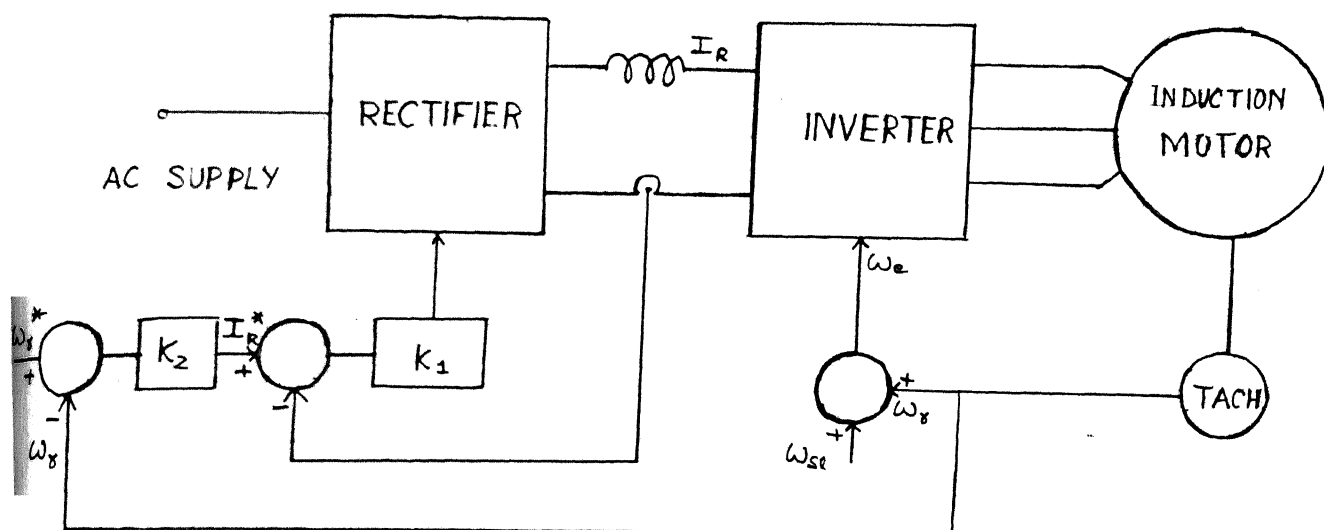


Fig. 4.7 Independent speed and slip frequency control using proportional controller.

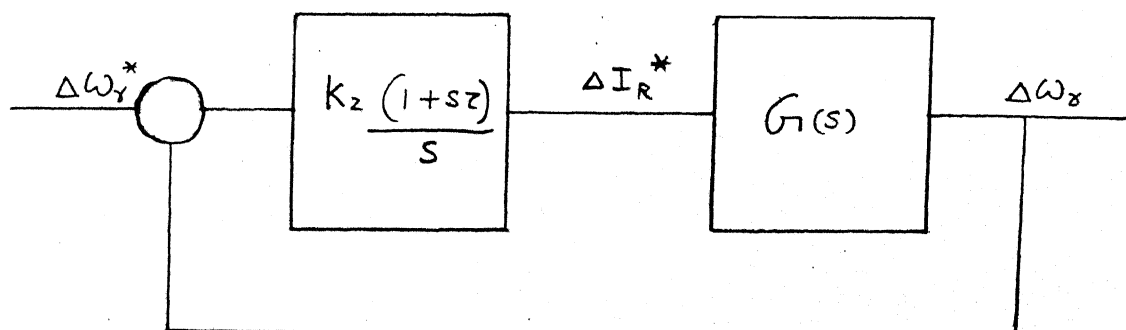
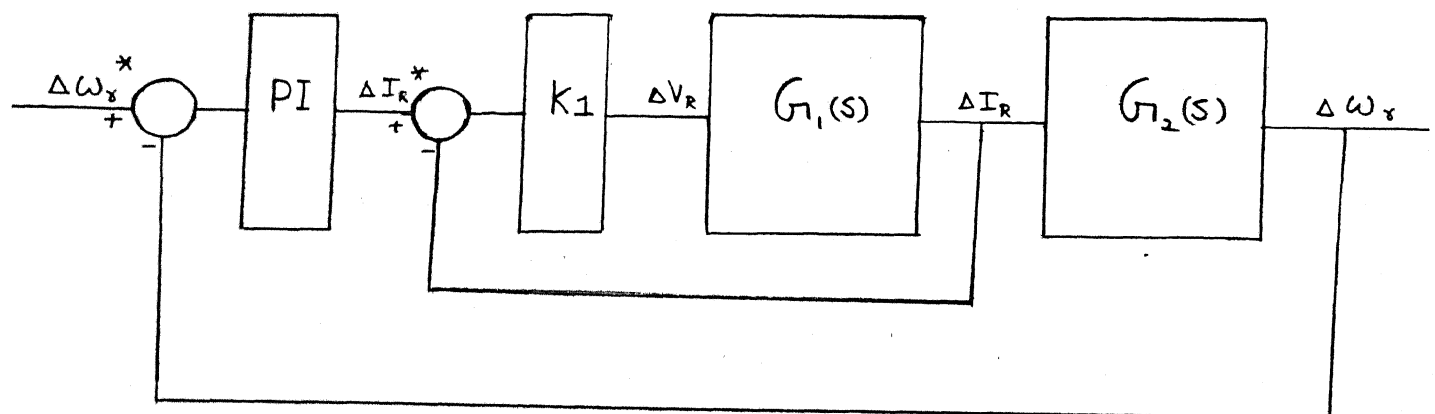
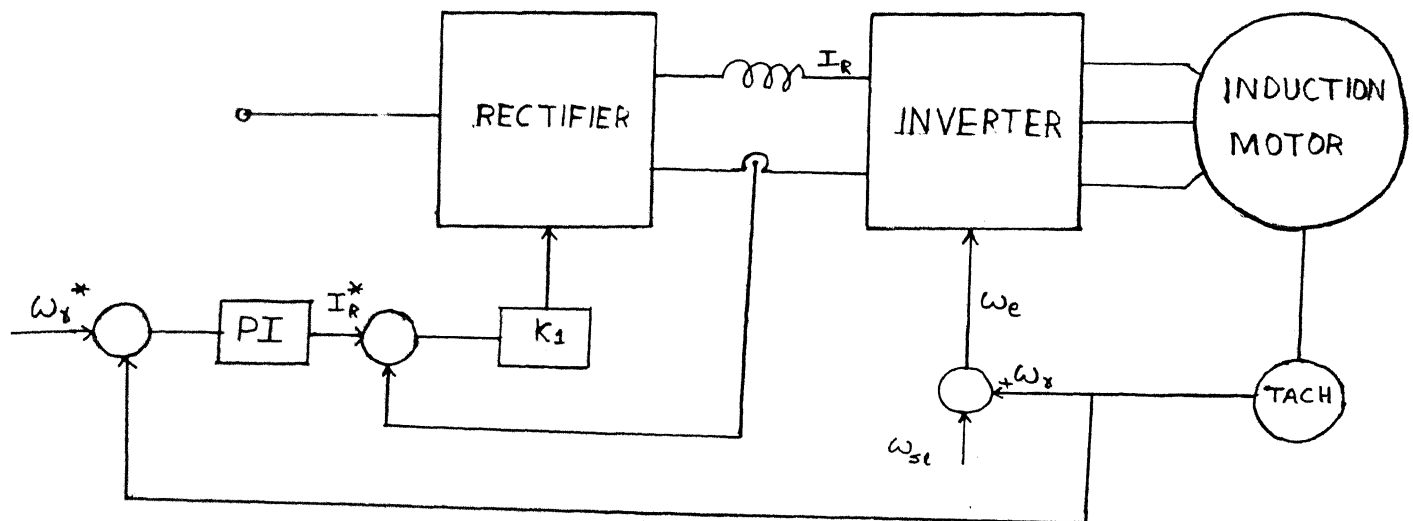


Fig. 4.8 Independent speed and slip frequency control using proportional plus integral controller.

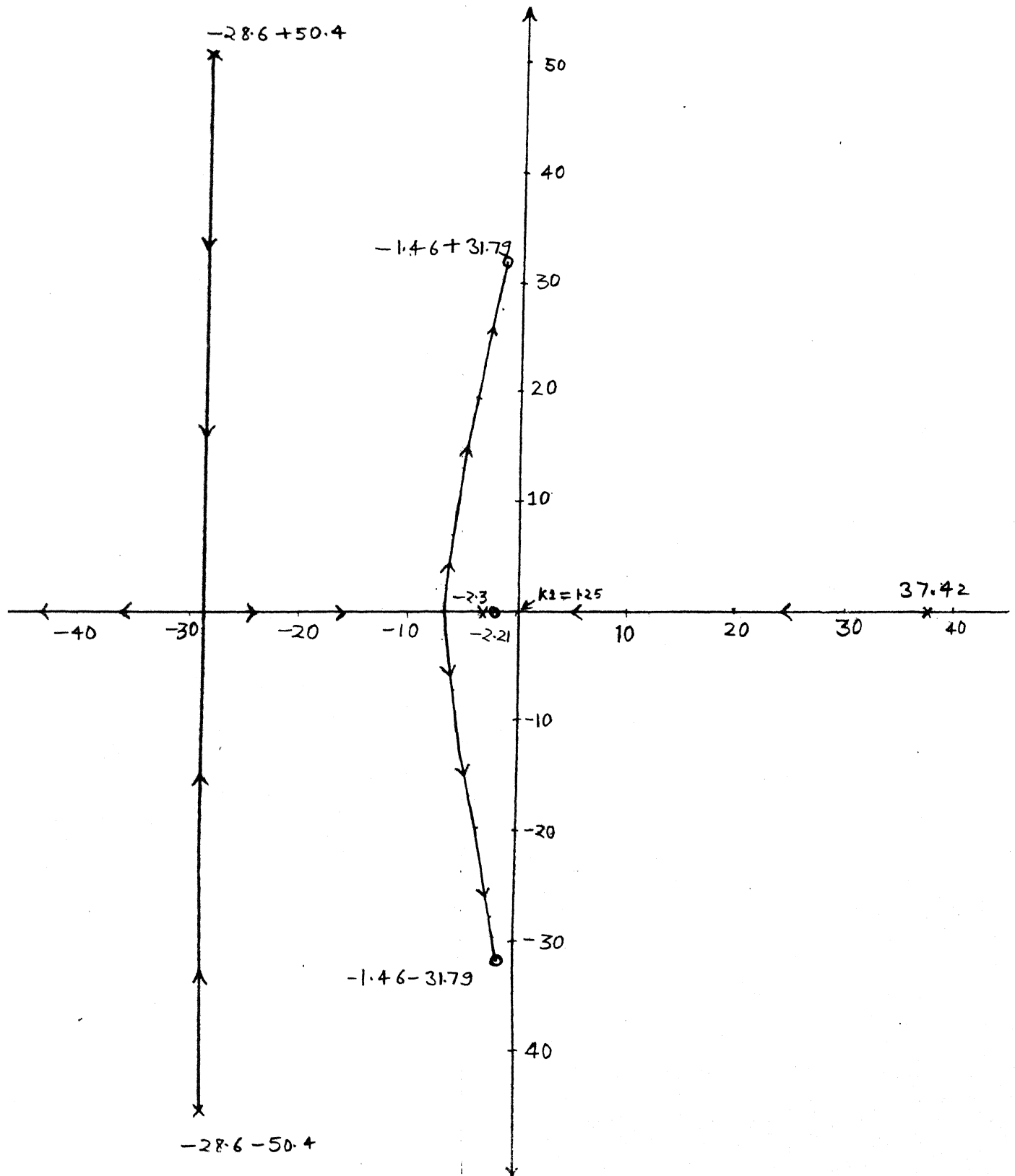


Fig. 4.9 Root locus plot for $\Delta I_R' / \Delta V_R'$, slip = 0.003,
 $I_R = 60\text{A}$; $f = 50\text{ Hz}$.

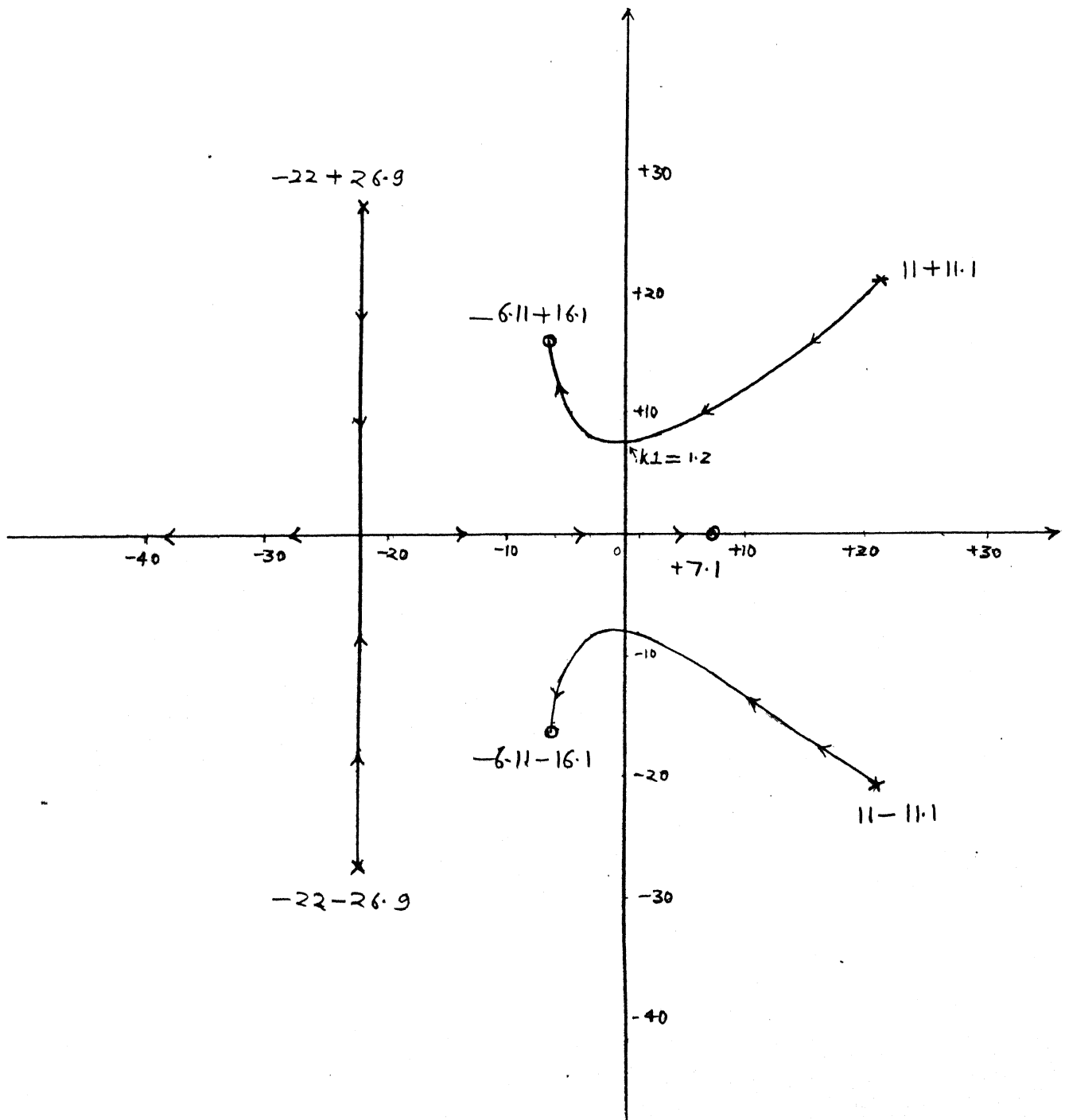


Fig. 4.10 Root locus plot for
 $\Delta I_R' / \Delta V_R'$; slip = 0.02
 $I_R = 60\text{A}$; $f = 50\text{ Hz}$.

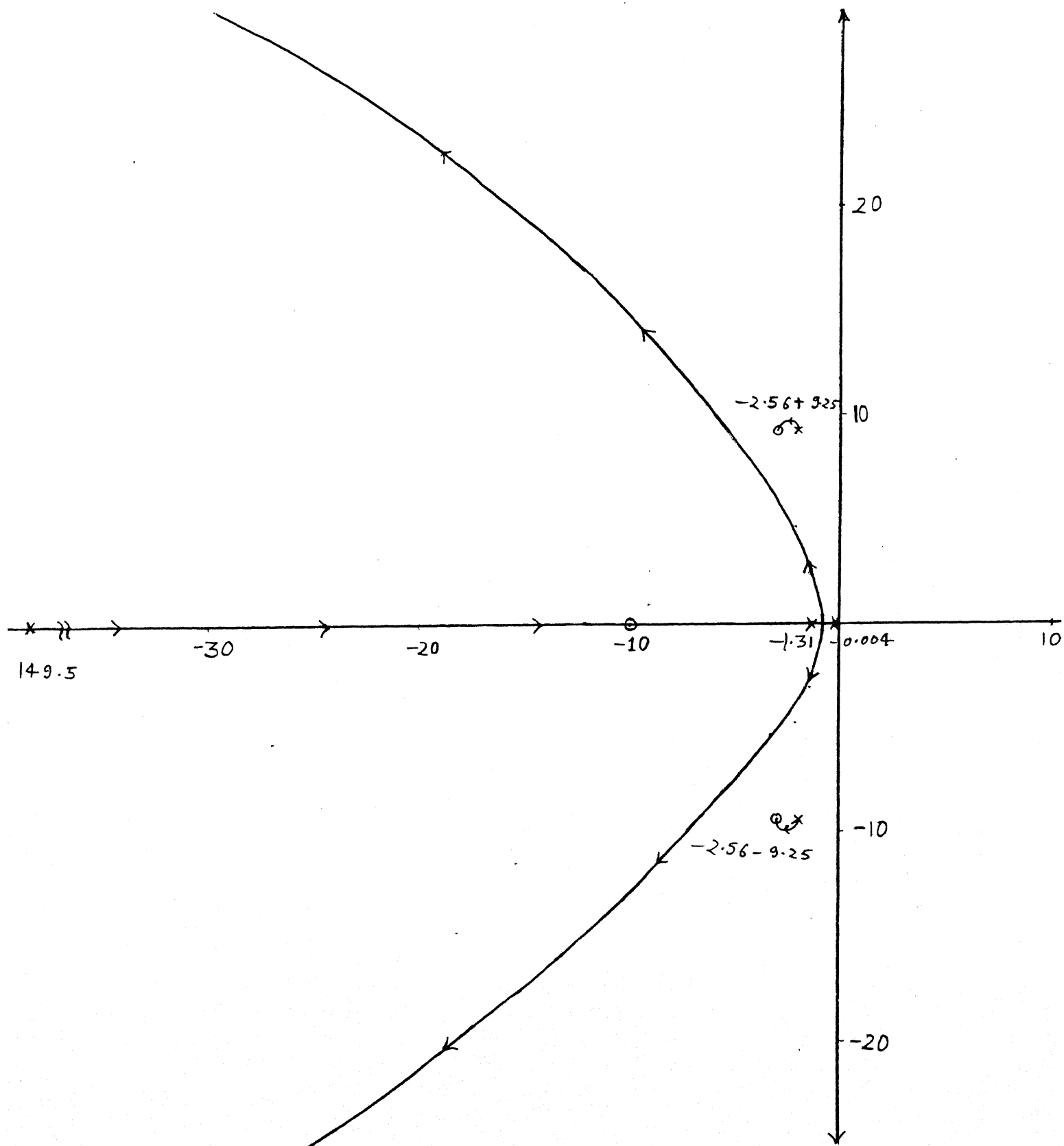


Fig. 4.12: Root locus plot for
 $\Delta\omega_r/\Delta\omega_r^*$; slip = 0.02

$I_r = 60A$; $K_r = 1.3$; $\tau = 0.1$

REFERENCE SPEED AND SLIP
 FREQUENCY CONTROL

CHAPTER 5

CONCLUSION

The steady-state characteristics of an induction motor fed with the current source inverter differ considerably from those for the same motor fed with the voltage source inverter. It was shown that current source inverter fed induction motor has certain advantages over the voltage source inverter fed induction motor.

The feasibility of developing controlled current induction motor drives using transfer function techniques has been studied. A dynamic linearized model was used as the basis of the transient response study. Open-loop operation is statically unstable for negative sloped portion and dynamically unstable for all operating points of the steady-state characteristic.

A systematic study of several controllers in a current source inverter fed induction motor drive and their effects on the dynamic response and stability of the system has been done in the current work reported in this thesis.

It has also been shown, that, independent current and slip frequency control is capable of stabilizing the drive system for all operating points. The drive system using speed and slip control is stable for all values gain for a given

frequency. The improvement in transient response was observed with closed loop operation compare to that of open loop operation.

It was shown that the system may or may not be stable for various values of gain and use of adaptive controller was suggested. There exist essentially two approaches, namely identification and control (which is mainly digital) and the other is model reference adaptive control (which can be analog or digital). The main problem in identification and control is, that, one has to do on line identification and drive systems are not all that slow to allow this kind of control. However, work is to be done in this area. In model reference adaptive control one changes the controller parameters of the actual system in such a way that the system behaviour conforms to the reference model behaviour. We do not see simple solutions in this case. However, this area needs to be explored.

In the present work, we developed a broad base for analysing controlled current inverter fed induction motor. However, we could analyse the stability and transient response for independent current and slip control. The same analysis can be extended to flux control as well as to field oriented

control. The model developed can be used to determine stability region in the parameter space. Use of adaptive control viz. identification and control or model reference adaptive control should be studied.

equations (3.2), (3.3) and (3.4) into (AI.1), and again substituting the resulting equations into (AI.2), the fundamental components i_{qsl} , i_{dsl} , and the n th harmonic components i_{qsn} , i_{dsn} are described as

$$i_{qsl} = \frac{2\sqrt{3}}{\pi} I_R$$

$$i_{dsl} = 0 \quad (AI.3)$$

$$i_{qsn} = \begin{aligned} & \frac{1}{n} \frac{2\sqrt{3}}{\pi} I_R \cos(n+1)\omega t, \quad n=5,11,\dots, \\ & \frac{1}{n} \frac{2\sqrt{3}}{\pi} I_R \cos(n-1)\omega t, \quad n=7,13,\dots, \end{aligned} \quad (AI.4)$$

$$i_{dsn} = \begin{aligned} & \frac{1}{n} \frac{2\sqrt{3}}{\pi} I_R \sin(n+1)\omega t, \quad n=5,11,\dots, \\ & \frac{1}{n} \frac{2\sqrt{3}}{\pi} I_R \sin(n-1)\omega t, \quad n=7,13,\dots, \end{aligned} \quad (AI.5)$$

From (AI.4) - (AI.5), we get eqns. (3.37) and (3.38).

APPENDIX II

State-space representation of the system is represented in the state-space form as,

$$\dot{\underline{x}} = \underline{A}\underline{x} + \underline{B}\underline{u}$$

$$\underline{y} = \underline{C}\underline{x}$$

Assuming zero initial conditions, we get

$$T(s) = \frac{Y(s)}{U(s)} = C(SI - A)^{-1} B$$

$$T(s) = \frac{\beta_{n-1}S^{n-1} + \dots \beta_1S + \beta_0}{S^{n+\alpha_{n-1}}S^{n-1} + \dots \alpha_1S + \alpha_0}$$

where β_i 's are the coefficients of the numerator polynomial and α_i 's are the coefficients of the denominator polynomial.

Consider the constant $n \times n$ matrix A with characteristic polynomial.

$$\det(SI - A) = S^n + \alpha_{n-1}S^{n-1} + \dots \alpha_1S + \alpha_0$$

Then the resolvent of A can be written as

$$(SI - A)^{-1} = \frac{1}{\det(SI - A)} \sum_{i=1}^n S^{i-1} R_i$$

where the matrices R_i are given by

$$R_i = \sum_{j=1}^n \alpha_j A^{j-i}; \quad i = 1, 2, \dots, n$$

with $\alpha_n = 1$. The coefficients α_i and the matrices $R_i, i=1,2,\dots,n$ can be obtained through the following algorithms set

$$\alpha_n = 1, \quad R_n = I$$

then,

$$\alpha_{n-k} = \frac{-1}{K} \operatorname{tr} (AR_{n-k+1})$$

$$R_{n-k} = \alpha_{n-k} I + AR_{n-k+1}$$

$$\beta_{n-k} = C R_{n-k} B \quad [\text{By Tuel and Rane}]$$

for $K = 1,2,\dots,n$, for $K = n$, we have $R_0 = 0$

where $\operatorname{tr}(M) = \sum_{i=1}^n M_{ii}$.

This algorithm is known as Leverrier's algorithm. It is also as Sourian's method or Faddeeva's method. The fact that $R_0 = 0$ can be used as a numerical check. The algorithm is very convenient for a digital computer. The algorithm is relatively sensitive to round-off errors, and double precision is usually employed in the computations.

APPENDIX III

Name plate motor data

18 KW

4-pole

3-phase Y-connected

$\omega_b = 377 \text{ rad/sec}$

$J_{\text{Total}} = 0.31 \text{ Kg-m}^2$

$V_{\text{rated}} = 230\text{V rms}$

$I_{\text{rated}} = 64\text{A rms}$

Motor and filter parameters at $f = 60 \text{ Hz.}$

$r_s = 0.0788 \Omega$

$r_r' = 0.0408 \Omega$

$x_s = 5.7518 \Omega$

$x_r' = 6.0028 \Omega$

$x_m = 5.54 \Omega$

$X_F = 5.50 \Omega$

$R_F = 0.091 \Omega$

REFERENCES

- [1] B. Mokrytzki, 'The Controlled Slip Static Inverter Drive', IEEE Trans. on Industrial and General Applications, vol. IGA-4, No. 3, May/June, 1968.
- [2] T.A. Lipo and P.C. Krause, 'Stability Analysis of a Rectifier-Inverter Induction Motor Drive', IEEE Trans. on Power Apparatus and Systems, vol. PAS-88, No. 1, January, 1969.
- [3] P.C. Krause, and T.A. Lipo, 'Analysis and Simplified Representations of a Rectifier-Inverter Induction Motor Drive', IEEE Trans. on Power Apparatus and Systems, vol. PAS-88, No. 5, May, 1969.
- [4] T.A. Lipo, and E.P. Cornell, 'State-Variable Steady-State Analysis of a Controlled Current Induction Motor Drive', IEEE Trans. on Industry Applications, vol. IA-11, No. 6, November/December, 1975.
- [5] N. Sawaki and N. Sato, 'Steady-State and Stability Analysis of Induction Motor Driven by Current Source Inverter', IEEE Trans. on Industry Applications, vol. IA-13, No. 3, May/June, 1977.
- [6] E.P. Cornell and T.A. Lipo, 'Modelling and Design of Controlled Current Induction Motor Drive Systems', IEEE Trans. on Industry Applications, vol. IA-13, No. 4, July/August, 1977.
- [7] M.L. Macdonald and P.C. Sen, 'Control Loop Study of Induction Motor Drives using DQ Model', IEEE Trans. on Industrial Electronics and Control Instrumentation, vol. IECI-26, No. 4, Nov. 1979.
- [8] P.C. Krause and C.H. Thomas, 'Simulation of Symmetrical Induction Machinery', IEEE Trans. on Power Apparatus and Systems, vol. PAS-84, No. 11, November, 1965.
- [9] T.H. Barton, 'Variable frequency variable speed ac drive', Electric Machines and Power Systems, 12:143-163, 1987.
- [10] E.P. Cornell and T.A. Lipo, 'Design of controlled current ac drive systems using transfer function techniques', in Proc. IFAC Symp. Control in Power Electronics and Electrical Drives, vol. I, October, 1974.

- [11] T.A. Lipo and A.B. Plunbett, 'A novel approach to induction motor transfer function', IEEE Trans. on Power Apparatus and Systems, vol. PAS-93, No. 5, September/October, 1984.
- [12] T.A. Lipo and F.G. Turnbull, 'Analysis and comparison of two types of square-wave inverter drives', IEEE Trans. on Industrial Applications, Vol. IA-11, March/April, 1975.
- [13] T.A. Lipo, 'The analysis of induction motors with symmetrically triggered thyristors', IEEE Trans. Power Apparatus Systems, vol. PAS-90, March/April, 1971.
- [14] C.J. Amato, 'Variable speed with controlled slip induction motor', in Proc. IEEE Ind. Static Power Converter Conf., 1965.
- [15] W.G. Tuel, Jr., 'On the transformation to (phase variable) canonical form', IEEE Trans. Automatic Control, vol. AC-11, 1966.
- [16] D.S. Rane, 'A simplified transformation to (phase variable) canonical form', IEEE Trans. Automatic Control, vol. AC-11, 1966.
- [17] M.P. Kazonierkowski and H. Kopeke, 'A Simple Control System for Current Source Inverter Fed Induction Motor Drives', IEEE Trans. on Industrial Applications, vol. IA-21, May-June, 1985.
- [18] R.H. Pennington, Introductory Computer Methods and Numerical Analysis, New York: Macmillan, 1975.
- [19] I.J. Nagrath and D.P. Kothari, Electric Machines, Tata McGraw Hill, 1983.
- [20] Fitzgerald, Kingsley and Umans, Electric Machinery, Tata McGraw Hill, 1983.
- [21] L.P. Singh, Advanced Power System Analysis and Dynamics, Wiley Eastern Limited, New Delhi, 1983.

- [22] G.K. Dubey, Industrial Drives-I.
- [23] Bimal K. Bose, Adjustable Speed AC drive systems
IEEE, 1981.
- [24] Bimal K. Bose, Power electronics and AC drives.
Prentice-Hall.
- [25] G.K. Dubey, S.R. Doradla, A. Joshi and R.M.K. Sinha,
Thyristorised Power Controllers, New Delhi, 1986
- [26] M.M. Choudhary, M.Tech. Thesis, I.I.T. Kanpur, 1983.
- [27]

APPENDIX IV

```

*****
THIS PROGRAM GETS THE TRANSFER FUNCTIONS IR/IR*, WR/WSL, IR/VR
WITH INDEPENDENT CURRENT AND FREQUENCY CONTROL
IT ALSO DETERMINES THE POLES AND ZEROS OF THE
ABOVE TRANSFER FUNCTIONS.
*****
DIMENSION A(1,4), WKSPACE(4), E(4,4), G(4,1), D(4,1)
DIMENSION RC(4), RI(1), AA(4,4), BB(4,1), B(4,1)
DIMENSION Z(1), INTEGE(4), C(1,4), NUMR(5), DEN(5)
DIMENSION RZ(4), IZ(4), RZ(4), IZ(4), H(4,4)
READ L1
OPEN(UNIT=1, DEVICE='DSK', FILE='INPUT.DAT')
OPEN(UNIT=6, DEVICE='DSK', FILE='ERROR.DAT')
OPEN(UNIT=11, DEVICE='DSK', FILE='OUTPUT.DAT')
READ(40,*) ((C(IA,N),N=1,4),IA=1,4)
READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
IA=4; IB=4; IC=1; N=4
FQ=50; CIR=60; S=0.003
READ(05,*) FQ,S,CIR,L1
READ(05,*) L1
WRITE(05,*) FQ,S,CIR,L1
WRITE(41,97)
FORMAT(1X, '////////')
WRITE(41,95)
FORMAT(10X, '*****',/)
WRITE(41,94)
FORMAT(10X, 'THE TRANSFER FUNCTION IR/IR* USING P CONTROLLER',/)
WRITE(41,96)
FORMAT(10X, '*****',/)
WRITE(41,92)
FORMAT(10X, 'FREQUENCY',4X, 'SLIP',6X, 'CURRENT',6X, 'GAIN',/)
WRITE(41,93) FQ,S,CIR,L1
FORMAT(5X,4F12.4,/)
CQS=1.10266*CIR; P=4.0; WB=60.0*6.2832; WE=6.2832*FQ; RJ=0.31
RS=0.0788; R2=0.0408; SL=5.7518/WB; RL=6.0028/WB; CM=5.54/WB
FL=5.5/WB; RF=0.091; RF1=0.5483*RF; FL1=0.5483*FL; F=SL+FL1
R1=RS+RF1; CL=(F+RL-CM*CM); WR=WE-S*WE; WSL=WE-WR
E(1,3)=CM*WE; E(2,3)=RL*S*WE
E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS
G(1,1)=-R1*CQS; G(3,1)=CM*S*CQS*WE
*****THE EQUATION IS [A11][X]=[B]*****
WRITE(41,12)
FORMAT(20X, 'THE MATRIX [A11] IS',/)
WRITE(41,13) ((C(IA,N),N=1,4),IA=1,4)
FORMAT(10X,4F10.4,/)
WRITE(41,14)
FORMAT(10X, 'THE MATRIX [B] IS',/)
WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
FORMAT(10X,4F10.4,/)
*****FINDS STEADY STATE OPERATING POINT *****
WRITE(41,19)
FORMAT(15X, 'THE STEADY STATE OPERATING POINT IS')
CALL F04AEF(E,4,G,4,4,1,D,4,WKSPACE,AA,4,BB,4,0)
D(1,1)=1.654*D(1,1)
WRITE(41,16)
FORMAT(4X, 'VOLTAGE',4X, 'IDRO',9X, 'IDRO',5X, 'TORQUE',/)
WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
FORMAT(1X,4F10.2)
R=R1+L1
R=R1
A(1,1)=-(RL*R)/CL; A(1,2)=CM*R2/CL; A(1,3)=-CM*RL*WR/CL
A(1,4)=-CM*RL*D(3,1)/CL; A(2,1)=CM*R/CL; A(2,2)=-F*R2/CL
A(2,3)=RL*F*WR/CL-WE; A(2,4)=(RL*F*D(3,1)/CL)
A(3,1)=CM*SL/RL; A(3,2)=WSL; A(3,3)=-R2/RL
A(3,4)=-(CM*CQS+RL*D(2,1))/RL
A(4,1)=3*F*D(3,1)/(B*RJ); A(4,2)=0
A(4,3)=(3*F*P*CM*CQS)/(B*RJ); A(4,4)=0
DO 3 J=1,4
DO 4 J=1,4
H(1,J)=A(1,J)
CONTINUE
CONTINUE
WRITE(41,73)
FORMAT(20X, 'THE MATRIX [A] IS',/)
WRITE(41,74) ((A(I,K),K=1,4),I=1,4)
FORMAT(10X,4F16.4,/)
B(1,1)=CL*RL/CL; B(2,1)=-L1*CM/CL; B(3,1)=0; B(4,1)=0
B(1,1)=RL/CL; B(2,1)=-CM/CL; B(3,1)=0; B(4,1)=0
B(1,1)=0; B(2,1)=-D(3,1); B(3,1)=(CM*CQS+RL*D(2,1))/RL; B(4,1)=0
WRITE(41,21)
FORMAT(20X, 'THE MATRIX [B] IS',/)

```

```

C(1,1)=9;C(1,2)=0;C(1,3)=0;C(1,4)=1
C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
WRITE(41,23)
FORMAT(20X,'THE MATRIX [C] IS',/)
WRITE(41,24) ((C(N,K),K=1,4),N=1,1)
FORMAT(20X,'1*4F4.1',/)
CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
WRITE(41,31)
FORMAT(10X,'THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC',/)
WRITE(41,11)(NUMR(I),I=1,INUM)
WRITE(41,32)
FORMAT(10X,'THE COEFFICIENTS OF THE DEN IN THE TRANSFER FUNC',/)
WRITE(41,11)(DEN(I),I=1,5)
FORMAT(1X,5F15.6)
CALL FO2AFF(N,4,4,RR,RI,INTEGE,0)
WRITE(41,81)
FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
WRITE(41,83) (RR(N),RI(N),N=1,4)
FORMAT(10X,2F16.4)
WRITE(41,98)
FORMAT(1X,2(/////////))
CALL CO2AEF(DEN,5,REZ,IMZ,TOL,0)
WRITE(41,75)
FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
FORMAT(10X,2F16.4)
CALL CO2AEF(NUMR,INUM,RZ,IZ,TOL,0)
WRITE(41,77)
FORMAT(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,78) (RZ(I),IZ(I),I=1,3)
FORMAT(10X,2F16.4)
STOP
END
SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
REAL NUMR(5),DEN(5)
REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
DATA EPS/D.000001/
IFAIL = 1
IF( N .LE. 0 ) RETURN
IFAIL = 2
DO 10 I = 1,N
  IF(B(I,1) .NE. 0.0) GOTO 35
CONTINUE
RETURN
DO 20 I = 1,N
DO 20 J = 1,N
  R(I,J) = 0.0
  R(I,I) = 1.0
CONTINUE
DEN(1) = 1.0
DO 50 K = 1,N
CALL FOICKF(TMP1,R,B,4,4,4,Z,1,1,0)
CALL FOICKF(TMP2,C,TMP1,1,1,4,Z,1,1,0)
NUMR(K) = TMP2(1,1)
CALL FOICKF(TMP1,A,R,4,4,4,Z,1,1,0)
ALPHAK = -TRACE(TMP1,4,4)/K
DEN(K+1) = ALPHAK
DO 40 I = 1,N
  DO 30 J = 1,N
    R(I,J) = TMP1(I,J)
  IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
CONTINUE
CONTINUE
DO 60 I = 1,N
  IF(CABS(NUMR(I)) .GT. EPS ) GOTO 22
CONTINUE
INUM = 0
DO 70 I = 1,N
  INUM = INUM + 1
  NUMR(INUM) = NUMR(I)
CONTINUE
RETURN
END

```

```
DO 56 I=1,N  
TRACE=TRACE+c(I,I)  
CONTINUE  
RETURN  
END
```

THE TRANSFER FUNCTION IN/IR* USING P*CO NTROLLER

FREQUENCY	SLIP	CURRENT	GAIN
50.0000	0.0230	60.0000	1.3000

THE MATRIX [A11] IS

-1.0000	0.0000	4.6167	0.0000
0.0000	0.0408	0.0150	0.0000
0.0000	-0.0150	0.0408	0.0000
0.0000	0.0000	2.9167	-1.0000

THE MATRIX [B] IS

-8.5144
0.0000
0.9163
0.0000

THE STEADY STATE OPERATING POINT IS

VOLTAGE	IDR3	IDR0	TORQUE
165.14	-7.28	19.78	57.70

THE MATRIX [A] IS

-147.3790	3.8843	-14.8097	-29.9881
136.0165	-6.1472	37.2607	47.4583
0.8698	0.9425	-2.5623	-53.7826
5.6255	0.0000	18.8174	0.0000

THE MATRIX [B] IS

134.1032
-123.7642
0.0000
0.0000

THE MATRIX [C] IS

1	0	0	0.3
---	---	---	-----

THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC

134.103240 687.238860 136718.730000 30.0711.450000

THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC

1.000000 155.038500 1952.691900 1335.023000 11166.964000

THE POLES OF THE MATRIX [A] ARE

-143.1214	0.0000
-0.9087	0.0000
-0.0292	7.0364
-0.0292	-7.0364

THE POLES OF THE TRANSFER FUNCTION ARE

-143.1214	0.0000
-6.6292	-7.0364
-6.6292	7.0364
-0.9087	0.0000

THE ZEROS OF THE TRANSFER FUNCTION ARE

-1.1556	-31.7953
-1.4556	31.7953
-2.2135	0.0000

C
C
C
C
C

```
*****
THIS PROGRAM GETS THE TRANSFER FUNCTIONS IR/IR*, WR/WSL, IR/VR
WITH INDEPENDENT CURRENT AND SLIP FREQUENCY CONTROL
IT ALSO DETERMINES THE POLES AND ZEROES OF THE
ABOVE TRANSFER FUNCTIONS.
*****
DIMENSION A(4,4), WKSPACE(4), E(4,4), G(4,1), D(4,1)
DIMENSION RR(4), RI(4), AA(4,4), BB(4,1), B(4,1)
DIMENSION Z(1), INTEGE(4), C(1,4), NUMR(5), DEN(5)
DIMENSION REZ(4), IMZ(4), RZ(4), IZ(4), H(4,4)
REAL L1
OPEN(UNIT=40, DEVICE='DSK', FILE='INPUT.DAT')
OPEN(UNIT=6, DEVICE='DSK', FILE='ERROR.DAT')
OPEN(UNIT=41, DEVICE='DSK', FILE='OUTPUT.DAT')
READ(40,*) ((E(IA,N), N=1,4), IA=1,4)
READ(40,*) ((G(IB,M), IB=1,4), M=1,1)
IA=1; IB=4; IC=1; N=4
FJ=50; CIR=60; S=0.003
READ(05,*) L1
READ(05,*) FQ, S, CIR, L1
WRITE(05,*) FQ, S, CIR, L1
WRITE(41,97)
FORMAT(1X, '////////')
WRITE(41,95)
FORMAT(10X, '*****',/)
WRITE(41,94)
FORMAT(10X, 'THE TRANSFER FUNCTION IR/IR* USING P CONTROLLER',/)
WRITE(41,96)
FORMAT(10X, '*****',/)
WRITE(41,92)
FORMAT(10X, 'FREQUENCY', 4X, 'SLIP', 6X, 'CURRENT', 6X, 'GAIN',/)
WRITE(41,93) FQ, S, CIR, L1
FORMAT(5X, 4F12.4,/)
CQS=1.10266*CIR; P=4.0; WB=60.0*6.2832; WE=6.2832*FQ; RJ=0.31
RS=0.0788; R2=0.0408; SL=5.7518/WB; RL=6.0028/WB; CM=5.54/WB
FL=5.5/WB; RF=0.091; RF1=0.5483*RF; FL1=0.5483*FL; F=SL+FL1
R1=RS+RF1; CL=(F*RL-CM*CM); WR=WE-S*WE; WSL=WE-WR
E(1,3)=CM*WE; E(2,3)=RL*S*WE
E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS
G(1,1)=-R1*CQS; G(3,1)=CM*S*CQS*WE
*****THE EQUATION IS [A11][X]=[B]*****
WRITE(41,12)
FORMAT(20X, 'THE MATRIX [A11] IS',/)
WRITE(41,13) ((E(IA,N), N=1,4), IA=1,4)
FORMAT(10X, 4F10.4,/)
WRITE(41,14)
FORMAT(10X, 'THE MATRIX [B] IS',/)
WRITE(41,15) ((G(IB,M), M=1,1), IB=1,4)
FORMAT(10X, F10.4,/)
***** FINDS STEADY STATE OPERATING POINT *****
WRITE(41,19)
FORMAT(15X, 'THE STEADY STATE OPERATING POINT IS')
CALL F04AEF(E, 4, G, 4, 1, D, 4, WKSPACE, AA, 4, BB, 4, 0)
D(1,1)=1.654*D(1,1)
WRITE(41,16)
FORMAT(4X, 'VOLTAGE', 4X, 'IQDR', 8X, 'IDRO', 5X, 'TORQUE',/)
WRITE(41,17) ((D(IC,M), IC=1,4), M=1,1)
FORMAT(1X, 4F10.2)
R=R1+L1
B=R1
A(1,1)=-(RL*R)/CL; A(1,2)=CM*R2/CL; A(1,3)=-CM*RL*WR/CL
A(1,4)=-CM*RL*U(3,1)/CL; A(2,1)=CM*R/CL; A(2,2)=-F*R2/CL
A(2,3)=RL*F*WR/CL-WE; A(2,4)=CM*CM*D(3,1)/CL
A(3,1)=CM*WSL/RL; A(3,2)=WSL; A(3,3)=-R2/RL
A(3,4)=0
A(4,1)=3*P*P*CM*D(3,1)/(B*RJ); A(4,2)=0
A(4,3)=(3*P*P*CM*CQS)/(B*RJ); A(4,4)=0
DO 3 J=1,N
DO 4 J=1,N
H(1,J)=A(1,J)
CONTINUE
CONTINUE
WRITE(41,73)
FORMAT(20X, 'THE MATRIX [A] IS',/)
WRITE(41,74) ((A(K,K), K=1,4), N=1,4)
FORMAT(10X, 4F10.4,/)
```

C

97

95

94

96

92

93

C

12

13

14

15

C

19

16

17

C

4

3

73

74


```

C      B(1,1)=L1*RL/CL;B(2,1)=-L1*CM/CL;B(3,1)=0;B(4,1)=0
C      B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
C      B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*COS+RL*D(2,1))/RL;B(4,1)=0
21     WRITE(41,21)
C      FORMAT(20X,'THE MATRIX [B] IS',/)
38     WRITE(41,38) ((B(N,K),K=1,1),N=1,4)
C      FORMAT(10X,F16.4,/)
C      C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
C      C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=1
23     WRITE(41,23)
C      FORMAT(20X,'THE MATRIX [C] IS',/)
24     WRITE(41,24) ((C(N,K),K=1,4),N=1,1)
C      FORMAT(20X,'[4F4.1]',/)
31     CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
C      WRITE(41,31)
C      FORMAT(10X,'THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC',/)
C      WRITE(41,11)(NUMR(I),I=1,INUM)
C      WRITE(41,32)
32     FORMAT(10X,'THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
C      WRITE(41,11)(DEN(I),I=1,5)
C      WRITE(41,98)
98     FORMAT(1X,2(//////////))
11     FORMAT(/(1X,5F15.6))
C      CALL FO2AFF(H,4,4,RR,RI,INTEGE,0)
C      WRITE(41,81)
81     FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
C      WRITE(41,83) (RR(N),RI(N),N=1,4)
83     FORMAT(10X,2F16.4)
C      CALL CO2AEF(DEN,5,REZ,IMZ,TOL,0)
C      WRITE(41,75)
75     FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
C      WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
76     FORMAT(10X,2F16.4)
C      CALL CO2AEF(NUMR,INUM,RZ,IZ,TOL,0)
C      WRITE(41,77)
77     FORMAT(10X,'THE ZERGES OF THE TRANSFER FUNCTION ARE',/)
C      WRITE(41,78) (RZ(I),IZ(I),I=1,3)
78     FORMAT(10X,2F16.4)
C      STOP
C      END
C      *****
C      THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF NUM & DEN
C      OF THE TRANSFER FUNCTION.
C      *****
C      SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
C      REAL NUMR(5),DEN(5)
C      REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
C      DATA EPS/0.000001/
C      IFAIL = 1
C      IF( N .LE. 0 ) RETURN
C      IFAIL = 2
C      DO 10 I = 1,N
C        IF(B(I,1) .NE. 0.0) GOTO 36
10     CONTINUE
C      RETURN
36     DO 20 I = 1,N
C        DO 20 J = 1,N
C          R(I,J) = 0.0
C          R(1,1) = 1.0
20     CONTINUE
C      DEN(1) = 1.0
C      DO 30 K = 1,N
C        CALL FO1CKF(TMP1,R,B,4,1,4,Z,1,1,0)
C        CALL FO1CKF(TMP2,C,TMP1,1,1,4,4,1,1,0)
C        NUMR(K) = TMP2(1,1)
C        CALL FO1CKF(TMP1,A,R,4,4,4,Z,1,1,0)
C        ALPHAK = -TRACE(TMP1,4,4)/K
C        DEN(K+1) = ALPHAK
C      DO 40 I = 1,N
C        DO 30 J = 1,N
C          R(I,J) = TMP1(I,J)
C        IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
30     CONTINUE
40     CONTINUE
50     CONTINUE

```

182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208

60
22

70

50

```
DO 60 I = 1,N
  IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
CONTINUE
INUM = 0
DO 70 J = 1,N
  INUM = INUM + 1
  NUMR(INUM) = NUMR(J)
CONTINUE
RETURN
END
FUNCTION TRACE(A,IA,N)
REAL A(4,4)
TRACE=0.0
DO 50 I=1,N
  TRACE=TRACE+A(I,1)
CONTINUE
RETURN
END
```

THE TRANSFER FUNCTION IR/IR* USING P CONTROLLER

FREQUENCY	SLIP	CURRENT	GAIN
50.0000	0.0030	60.0000	1.3000

THE MATRIX [A11] IS

-1.0000	0.0000	4.6167	0.0000
0.0000	0.0408	0.0150	0.0000
0.0000	-0.0150	0.0408	0.0000
0.0000	0.0000	2.9167	-1.0000

THE MATRIX [B] IS

-8.5144
0.0000
0.9163
0.0000

THE STEADY STATE OPERATING POINT IS

VOLTAGE	IDRO	IDRO	TORQUE
165.14	-7.28	19.78	57.70

THE MATRIX [A] IS

-147.3790	3.8843	-474.8097	-29.9881
136.0165	-6.1472	437.2607	27.6761
0.8698	0.9425	-2.5623	0.0000
5.6266	0.0000	18.8174	0.0000

THE MATRIX [B] IS

134.1032
-123.7642
0.0000
0.0000

THE MATRIX [C] IS

[1. 0. 0. 0.]

THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC

134.103240	687.238860	999.591420	0.060263
------------	------------	------------	----------

THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC

1.000000	150.088500	940.642240	3024.664200	2515.404000
----------	------------	------------	-------------	-------------

THE POLES OF THE MATRIX (A) ARE

-149.9492	0.0000
-2.4791	2.8386
-2.4791	-2.8386
-1.1810	0.0000

THE POLES OF THE TRANSFER FUNCTION ARE

-149.9492	0.0000
-2.4791	-2.8386
-2.4791	2.8386
-1.1811	0.0000

THE ZEROS OF THE TRANSFER FUNCTION ARE

-2.5623	-0.9424
-2.5623	0.9424
-0.0001	0.0000


```

*****
THIS PROGRAM GETS THE TRANSFER FUNCTIONS WR/WR*, WR/WE
WITH INDEPENDENT CURRENT AND FREQUENCY CONTROL USING
PROPORTIONAL CONTROLLER. IT ALSO DETERMINES THE
POLES AND ZEROS OF THE ABOVE TRANSFER FUNCTIONS.
*****
DIMENSION A(4,4),WKSPCE(4),E(4,4),G(4,1),D(4,1)
DIMENSION R(4),R1(4),AA(4,4),BB(4,1),B(4,1)
DIMENSION Z(1),INTEGE(4),C(1,4),NUMR(5),DEN(5)
DIMENSION REZ(4),IMZ(4),RZ(4),IZ(4),H(4,4)
REAL L1,L2
OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
IA=4;IB=4;IC=1;N=4
FQ=50;CIR=60;S=0.003
READ(05,*) FQ,S,CIR,L1,L2
READ(05,*) L1
WRITE(05,*) FQ,S,CIR,L1,L2
WRITE(41,97)
FORMAT(1X,////////)
WRITE(41,95)
FORMAT(10X, '*****',/)
WRITE(41,94)
FORMAT(10X, 'THE TRANSFER FUNCTION WR/WR* USING P CONTROLLER',/)
WRITE(41,96)
FORMAT(10X, '*****',/)
WRITE(41,92)
FORMAT(10X, 'FREQ',6X, 'SLIP',6X, 'CURR',6X, 'G1',6X, 'G2',/)
WRITE(41,93) FQ,S,CIR,L1,L2
FORMAT(5X,5F10.4,/)
CQS=1.10266*CIR; P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
RS=0.0788;RZ=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
R1=RS+RF1;CL=(F*RL-CM*CM);WR=WE-S*WE;WSL=WE-WR
E(1,3)=CM*WE; E(2,3)=RL*S*WE
E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS
G(1,1)=-R1*CQS; G(3,1)=CM*S*CQS*WE
*****THE EQUATION IS [A11]X=[B]*****
WRITE(41,12)
FORMAT(20X, 'THE MATRIX [A11] IS',/)
WRITE(41,13) ((E(IA,N),N=1,4),IA=1,4)
FORMAT(10X,4F10.4/)
WRITE(41,14)
FORMAT(10X, 'THE MATRIX [B] IS',/)
WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
FORMAT(10X,4F10.4,/)
***** FINDS STEADY STATE OPERATING POINT *****
WRITE(41,19)
FORMAT(15X, 'THE STEADY STATE OPERATING POINT IS')
CALL F04AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
D(1,1)=1.654*B(1,1)
WRITE(41,16)
FORMAT(4X, 'VOLTAGE',4X, 'IQRD',8X, 'IDRD',5X, 'TORQUE',/)
WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
FORMAT(1X,4F10.2)
R=R1+L1
R=R1
A(1,1)=- (RL*R)/CL; A(1,2)=CM*R2/CL; A(1,3)=-CM*RL*WR/CL
A(1,4)=-CM*RL*D(3,1)/CL-L1*RL/CL; A(2,1)=CM*R/CL; A(2,2)=-F*R2/CL
A(2,3)=RL*F*WR/CL-WE; A(2,4)=(RL*F*D(3,1)/CL)+L1*CM/CL
A(3,1)=CM*WSL/RL; A(3,2)=WSL; A(3,3)=-R2/RL
A(3,4)=- (CM*CQS+RL*D(2,1))/RL
A(4,1)=3*P*P*CM*D(3,1)/(8*RJ); A(4,2)=0
A(4,3)=(3*P*P*CM*CQS)/(8*RJ); A(4,4)=0
DO 3 J=1,N
DO 4 J=1,N
H(1,J)=A(1,J)
CONTINUE
CONTINUE
WRITE(41,73)
FORMAT(20X, 'THE MATRIX [A] IS',/)
WRITE(41,74) ((A(N,K),K=1,4),N=1,4)

```

```

74  FORMAT(10X,4F16.4,/)
    B(1,1)=L1*L2*RL/CL;B(2,1)=-L1*L2*CM/CL;B(3,1)=0;B(4,1)=0
C    B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
C    B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*CQS+RL*D(2,1))/RL;B(4,1)=0
    WRITE(41,21)
21  FORMAT(20X,'THE MATRIX [B] IS',/)
    WRITE(41,38) ((B(N,K),K=1,1),N=1,4)
38  FORMAT(10X,4F16.4,/)
    C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=1
C    C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
    WRITE(41,23)
23  FORMAT(20X,'THE MATRIX [C] IS',/)
    WRITE(41,24) ((C(N,K),K=1,4),N=1,1)
24  FORMAT(20X,'[4F4,]',/)
    CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
    WRITE(41,31)
31  FORMAT(10X,'THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC',/)
    WRITE(41,11)(NUMR(I),I=1,INUM)
    WRITE(41,32)
32  FORMAT(10X,'THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
    WRITE(41,11)(DEN(I),I=1,5)
11  FORMAT(7(1X,5F15.6))
    WRITE(41,98)
98  FORMAT(1X,2(//////////))
    CALL F02AEF(H,4,4,RR,RI,INTEGE,0)
    WRITE(41,81)
81  FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
    WRITE(41,83) (RR(N),RI(N),N=1,4)
83  FORMAT(10X,2F16.4)
    CALL C02AEF(DEN,5,REZ,IMZ,TOL,0)
    WRITE(41,75)
75  FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
    WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
76  FORMAT(10X,2F16.4)
    CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
    WRITE(41,77)
77  FORMAT(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE',/)
    WRITE(41,78) (RZ(I),IZ(I),I=1,2)
78  FORMAT(10X,2F16.4)
    STOP
    END
C *****
C THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF NUM & DEN
C OF THE TRANSFER FUNCTION.
C *****
SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
    REAL NUMR(5),DEN(5)
    REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
    DATA EPS/0.000001/
    IFAIL = 1
    IF (N .LE. 0) RETURN
    IFAIL = 2
    DO 10 I = 1,N
        IF (B(I,1) .NE. 0.0) GOTO 36
    CONTINUE
    RETURN
36  DO 20 J = 1,N
        DO 20 I = 1,N
            R(I,J) = 0.0
            R(I,I) = 1.0
        CONTINUE
20  DEN(1) = 1.0
    DO 30 K = 1,N
        CALL F01CKF(TMP1,R,B,4,4,4,2,1,1,0)
        CALL F01CKF(TMP2,C,TMP1,1,1,4,2,1,1,0)
        NUMR(K) = TMP2(1,1)
        CALL F01CKF(TMP1,A,B,4,4,4,2,1,1,0)
        ALPHAK = -TRACE(TMP1,4,4)/K
        DEN(K+1) = ALPHAK
    DO 40 I = 1,N
        DO 30 J = 1,N
            R(I,J) = TMP1(I,J)
        IF (I.EQ.J) R(I,I)=R(I,I)+ALPHAK
    CONTINUE
40  CONTINUE

```

```

183      50      CONTINUE
184      DO 60 I = 1, N
185          IF (ABS(NUMR(I)) .GT. EPS ) GOTO 22
186      60      CONTINUE
187      INUM = 0
188      22      DO 70 J = I, N
189          INUM = INUM + 1
190          NUMR(INUM) = NUMR(J)
191      70      CONTINUE
192      RETURN
193      END
194      FUNCTION TRACE(A, IA, N)
195      REAL A(4,4)
196      TRACE=0.0
197      DO 56 I=1, N
198          TRACE=TRACE+A(I,1)
199      56      CONTINUE
200      RETURN
201      END
202
203

```

THE TRANSFER FUNCTION WR/VR* USING P CONTROLLER

FREQ	SLIP	CURR	G1	G2
50.0000	0.0030	60.0000	1.3000	1.0000

THE MATRIX [A11] IS

-1.0000	0.0000	4.6167	0.0000
0.0000	0.0408	0.0150	0.0000
0.0000	-0.0150	0.0408	0.0000
0.0000	0.0000	2.9167	-1.0000

THE MATRIX [B] IS

-8.5144
0.0000
0.9163
0.0000

THE STEADY STATE OPERATING POINT IS

VOLTAGE	IDRO	IDRO	TORQUE
165.14	-7.28	19.78	57.70

THE MATRIX [A] IS

-147.3790	3.8843	-474.8097	-164.0913
136.0165	-6.1472	437.2607	171.2226
0.8698	0.9425	-2.5623	-53.7826
5.6266	0.0000	18.8174	0.0000

THE MATRIX [B] IS

134.1032
-123.7642
0.0000
0.0000

THE MATRIX [C] IS

[0. 0. 0. 1.]

THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC

754.539430 3866.788100 11248.514000

THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC

1.000000 156.088500 2707.231300 17801.811000 22415.492000

THE POLES OF THE MATRIX [A] ARE

-137.3075	0.0000
-1.6224	0.0000
-8.5793	5.1979
-8.5793	-5.1979

THE POLES OF THE TRANSFER FUNCTION ARE

-137.3075	0.0000
-8.5793	-5.1979
-8.5793	5.1979
-1.6224	0.0000

THE ZEROES OF THE TRANSFER FUNCTION ARE

-2.5623	-2.8883
-2.5623	2.8883

```

*****
THIS PROGRAM GETS THE TRANSFER FUNCTIONS WR/WR*, WR/WSL
WITH INDEPENDENT SPEED AND SLIP FREQUENCY CONTROL USING
PROPORTIONAL (P) CONTROLLER. IT DETERMINES THE
POLES AND ZEROS OF THE ABOVE TRANSFER FUNCTIONS.
*****
DIMENSION A(4,4),WKSPCE(4),E(4,4),G(4,1),D(4,1)
DIMENSION RR(4),RI(4),AA(4,4),BB(4,1),B(4,1)
DIMENSION Z(1),INTEGE(4),C(1,4),NUMR(5),DEN(5)
DIMENSION REZ(4),IMZ(4),RZ(4),IZ(4),H(4,4)
REAL L1,L2
OPEN(UNIT=4,DEVICE='DSK',FILE='INPUT.DAT')
OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
OPEN(UNIT=11,DEVICE='DSK',FILE='OUTPUT.DAT')
READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
IA=4;IB=4;IC=1;N=4
FQ=50;CIR=60;S=0.02;L1=1.3
READ(05,*) FQ,S,CIR,L1,L2
READ(05,*) L2
WRITE(05,*) FQ,S,CIR,L1,L2
WRITE(41,97)
FORMAT(1X,////////)
WRITE(41,95)
FORMAT(10X, '*****',/)
WRITE(41,94)
FORMAT(10X, 'THE TRANSFER FUNCTION WR/WR* USING P CONTROLLER',/)
WRITE(41,96)
FORMAT(10X, '*****',/)
WRITE(41,92)
FORMAT(10X, 'FREQ',6X,'SLIP',6X,'CURR',6X,'G1',6X,'G2',/)
WRITE(41,93) FQ,S,CIR,L1,L2
FORMAT(5X,5F10.4,/)
COS=1.10266*CIR; P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
RI=RS+RF1;CL=(F*RL-CM*CM);WR=WE-S*WE;WSL=WE-WR
E(1,3)=CM*WE; E(2,3)=RL*S*WE
E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*COS
G(1,1)=-RI*COS; G(3,1)=CM*S*COS*WE
*****THE EQUATION IS [A11](X)=[B]*****
WRITE(41,12)
FORMAT(20X, 'THE MATRIX [A11] IS',/)
WRITE(41,13) ((E(IA,N),N=1,4),IA=1,4)
FORMAT(10X,4F10.4,/)
WRITE(41,14)
FORMAT(10X, 'THE MATRIX [B] IS',/)
WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
FORMAT(10X,4F10.4,/)
*****FINDS STEADY STATE OPERATING POINT *****
WRITE(41,19)
FORMAT(15X, 'THE STEADY STATE OPERATING POINT IS')
CALL F04ABE(E,A,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
D(1,1)=1.654*D(1,1)
WRITE(41,16)
FORMAT(4X, 'VOLTAGE',4X,'IDRO',8X,'IDRO',5X,'TORQUE',/)
WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
FORMAT(1X,4F10.2)
R=R1+L1
H=R1
A(1,1)=-(R2*RI)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
A(1,4)=-CM*RL*D(3,1)/CL-L1*RL/CL;A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL
A(2,3)=RL*F*WR/CL-WE;A(2,4)=(CM*CM*D(3,1)/CL)+L1*CM/CL
A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL
A(3,4)=0
A(4,1)=3*P*P*CM*D(3,1)/(8*RJ);A(4,2)=0
A(4,3)=(3*P*P*CM*COS)/(8*RJ);A(4,4)=0
DO 3 I=1,4
DO 4 J=1,4
H(I,J)=A(I,J)
CONTINUE
CONTINUE
WRITE(41,73)
FORMAT(20X, 'THE MATRIX [A] IS',/)
WRITE(41,74) ((A(I,K),K=1,4),I=1,4)

```

```

FORMAT(10X,4F16.4,/)
B(1,1)=L1*L2*RL/CL;B(2,1)=-L1*L2*CM/CL;B(3,1)=0;B(4,1)=0
B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*CQS+RL*D(2,1))/RL;B(4,1)=0
WRITE(41,21)
FORMAT(20X,'THE MATRIX [B] IS',/)
WRITE(41,38) ((B(N,K),K=1,1),N=1,4)
FORMAT(10X,4F16.4,/)
C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=1
C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
WRITE(41,23)
FORMAT(20X,'THE MATRIX [C] IS',/)
WRITE(41,24) ((C(N,K),K=1,4),N=1,1)
FORMAT(20X,'1'4F4,1J2,/)
CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
WRITE(41,31)
FORMAT(10X,'THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC',/)
WRITE(41,11)(NUMR(I),I=1,INUM)
WRITE(41,32)
FORMAT(10X,'THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
WRITE(41,11)(DEN(I),I=1,5)
FORMAT(/(1X,5F15.6))
WRITE(41,98)
FORMAT(1X,2(//////////))
CALL F02AFF(H,4,4,RR,R1,INTEGE,0)
WRITE(41,81)
FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
WRITE(41,83)(RR(N),R1(N),N=1,4)
FORMAT(10X,2F16.4)
CALL C02AEF(DEN,5,REZ,IMZ,TOL,0)
WRITE(41,75)
FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,76)(REZ(N),IMZ(N),N=1,4)
FORMAT(10X,2F15.4)
CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
WRITE(41,77)
FORMAT(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,78)(RZ(I),IZ(I),I=1,2)
FORMAT(10X,2F16.4)
STOP
END
*****
THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF NUM & DEN
OF THE TRANSFER FUNCTION.
*****
SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
REAL NUMR(5),DEN(5)
REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
DATA EPS/0.000001/
IFAIL = 1
IF(N.LE.0) RETURN
IFAIL = 2
DO 10 I = 1,N
  IF(B(I,1).NE.0.0) GOTO 36
CONTINUE
RETURN
DO 20 I = 1,N
DO 20 J = 1,N
  R(I,J) = 0.0
  R(I,I) = 1.0
CONTINUE
DEN(1) = 1.0
DO 50 K = 1,N
  CALL F01CKF(TMP1,R,B,4,4,4,Z,1,1,0)
  CALL F01CKF(TMP2,C,TMP1,1,1,4,Z,1,1,0)
  NUMR(K) = TMP2(1,1)
  CALL F01CKF(TMP1,A,R,4,4,4,Z,1,1,0)
  ALPHAK = -TRACE(TMP1,4,4)/K
  DEN(K+1) = ALPHAK
DO 40 I = 1,N
DO 30 J = 1,N
  R(I,J) = TMP1(I,J)
IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
CONTINUE
CONTINUE

```

THE TRANSFER FUNCTION WR/WR* USING P CONTROLLER

FREQ	SLIP	CURR	G1	G2
50.0000	0.0030	60.0000	1.3000	1.0000

THE MATRIX [A11] IS

-1.0000	0.0000	4.6167	0.0000
0.0000	0.0408	0.0150	0.0000
0.0000	-0.0150	0.0408	0.0000
0.0000	0.0000	2.9167	-1.0000

THE MATRIX [B] IS

-8.5144
0.0000
0.9163
0.0000

VOLTAGE THE STEADY STATE OPERATING POINT IS
IDRO IDRO TORQUE

165.14	-7.28	19.78	57.70
--------	-------	-------	-------

THE MATRIX [A] IS

-147.3790	3.8843	-474.8097	-164.0913
136.0165	-6.1472	437.2607	151.4403
0.8698	0.9425	-2.5623	0.0000
5.6266	0.0000	18.8174	0.0000

THE MATRIX [B] IS

134.1032
-123.7642
0.0000
0.0000

THE MATRIX [C] IS

[0. 0. 0. 1.]

THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC

754.539430 3866.788100 11248.513000

THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC

1.000000	156.788500	1695.181700	6891.452300	13763.917000
----------	------------	-------------	-------------	--------------

THE POLES OF THE MATRIX I_A ARE

-144.6978	0.0000
-2.5177	2.9374
-2.5177	-2.9374
-6.3552	0.0000

THE POLES OF THE TRANSFER FUNCTION ARE

-144.6978	0.0000
-2.5177	-2.9374
-2.5177	2.9374
-6.3552	0.0000

THE ZEROS OF THE TRANSFER FUNCTION ARE

-2.5623	-2.8883
-2.5623	2.8883

```

CONTINUE
DO 60 I = 1,N
  IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
CONTINUE
INUM = 0
DO 70 J = 1,N
  INUM = INUM + 1
  NUMR(INUM) = NUMR(J)
CONTINUE
RETURN
END
FUNCTION TRACE(A,IA,N)
REAL A(4,4)
TRACE=0.0
DO 56 I=1,N
  TRACE=TRACE+A(I,I)
CONTINUE
RETURN
END

```


C
C
C
C
C

```
*****
THIS PROGRAM GETS THE TRANSFER FUNCTIONS WR/WR* , WR/WE
WITH INDEPENDENT SPEED AND FREQUENCY CONTROL USING PROPORTIONAL
PLUS INTEGRAL PROPORTIONAL CONTROLLER. IT ALSO DETERMINES THE
POLES AND ZEROES OF THE ABOVE TRANSFER FUNCTIONS.
*****
```

```
DIMENSION A(5,5),WKSPACE(4),E(4,4),G(4,1),D(4,1)
DIMENSION RR(5),RI(5),AA(4,4),BB(4,1),B(5,1)
DIMENSION Z(1),INTEGE(5),C(1,5),NUMR(5),DEN(6)
DIMENSION REZ(5),IMZ(5),RZ(5),IZ(5),H(5,5)
```

```
REAL L1,L2
OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
READ(40,*) ((G(IB,M),M=1,4),IB=1,4),M=1,1)
IA=5;IB=5;IC=1;N=5
```

```
FL=50;CIR=60;S=0.003;L1=1.3
READ(05,*) FQ,S,CIR,L1,L2,T2
READ(05,*) L1
WRITE(05,*) FQ,S,CIR,L1,L2,T2
```

```
WRITE(41,97)
```

```
FORMAT(1X,////////)
```

```
WRITE(41,95)
```

```
FORMAT(10X, '*****',/
```

```
WRITE(41,94)
```

```
FORMAT(10X, 'THE TRANSFER FUNCTION WR/WR* USING PI CONTROLLER',/
```

```
WRITE(41,96)
```

```
FORMAT(10X, '*****',/
```

```
WRITE(41,92)
```

```
FORMAT(10X, 'FREQ',6X,'SLIP',6X,'CUR',6X,'G1',8X,'G2',8X,'T2',/)
```

```
WRITE(41,93) FQ,S,CIR,L1,L2,T2
```

```
FORMAT(5X,6F10.4,/)
CQS=1.10266*CIR; P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
```

```
RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
```

```
FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
```

```
RI=RS+RF1;CL=(F*RL-CM*CM);WR=WE-S*WE;WSL=WE-WR
```

```
C(1,3)=CM*WE; E(2,3)=RL*S*WE
```

```
E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS
```

```
G(1,1)=-RI*CQS; G(3,1)=CM*S*CQS*WE
```

```
*****THE EQUATION IS LA111[X]=[B]*****
```

```
WRITE(41,12)
```

```
FORMAT(20X, 'THE MATRIX [A11] IS',/)
```

```
WRITE(41,13) ((E(IA,N),N=1,4),IA=1,4)
```

```
FORMAT(10X,4F10.4/)
```

```
WRITE(41,14)
```

```
FORMAT(7(10X, 'THE MATRIX [B] IS',/)
```

```
WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
```

```
FORMAT(10X,4F10.4,/)
***** FINDS STEADY STATE OPERATING POINT *****
```

```
WRITE(41,19)
```

```
FORMAT(7(10X, 'THE STEADY STATE OPERATING POINT IS'))
```

```
CALL F04AEF(E,4,G,4,4,1,D,4,WKSPACE,AA,4,BB,4,0)
```

```
D(1,1)=1.654*D(1,1)
```

```
WRITE(41,16)
```

```
FORMAT(4X, 'VOLTAGE',4X,'IDRO',8X,'IDRO',5X,'TORQUE',/)
```

```
WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
```

```
FORMAT(1X,4F10.2)
```

```
R=R1+L1
```

```
R=R1
```

```
A(1,4)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
```

```
A(1,5)=L1*RL/CL;A(1,5)=-((CM*RL*D(3,1)/CL)-(L1*L2*T2*RL)/CL
```

```
A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL;A(2,4)=-L1*CM/CL
```

```
A(2,3)=RL*F*WR/CL-WE;A(2,5)=(RL*F*D(3,1)/CL)+L1*L2*T2*CM/CL
```

```
A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL;A(3,4)=0
```

```
A(3,5)=-((CM*CQS+RL*D(2,1))/RL
```

```
A(3,4)=-((CM*CQS+RL*D(2,1))/RL
```

```
A(4,1)=0;A(4,2)=0;A(4,3)=0;A(4,4)=0;A(4,5)=-L2
```

```
A(5,1)=3*P*P*CM*D(3,1)/(B*RJ);A(5,2)=0
```

```
A(5,3)=(3*P*P*CM*CQS)/(B*RJ);A(5,4)=0;A(5,5)=0
```

```
DO 3 J=1,N
```

```
DO 4 J=1,N
```

```
H(1,J)=A(1,J)
```

```
CONTINUE
```

```
CONTINUE
```

```
WRITE(41,73)
```

C
C

97

95

94

96

92

93

C

12

13

14

15

C

19

16

17

C

C

4

3

```

095
096
097
098
099
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000
1001
1002
1003
1004
1005
1006
1007
1008
1009
1010
1011
1012
1013
1014
1015
1016
1017
1018
1019
1020
1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1090
1091
1092
1093
1094
1095
1096
1097
1098
1099
1100
1101
1102
1103
1104
1105
1106
1107
1108
1109
1110
1111
1112
1113
1114
1115
1116
1117
1118
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
1261
1262
1263
1264
1265
1266
1267
1268
1269
1270
1271
1272
1273
1274
1275
1276
1277
1278
1279
1280
1281
1282
1283
1284
1285
1286
1287
1288
1289
1290
1291
1292
1293
1294
1295
1296
1297
1298
1299
1300
1301
1302
1303
1304
1305
1306
1307
1308
1309
1310
1311
1312
1313
1314
1315
1316
1317
1318
1319
1320
1321
1322
1323
1324
1325
1326
1327
1328
1329
1330
1331
1332
1333
1334
1335
1336
1337
1338
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368
1369
1370
1371
1372
1373
1374
1375
1376
1377
1378
1379
1380
1381
1382
1383
1384
1385
1386
1387
1388
1389
1390
1391
1392
1393
1394
1395
1396
1397
1398
1399
1400
1401
1402
1403
1404
1405
1406
1407
1408
1409
1410
1411
1412
1413
1414
1415
1416
1417
1418
1419
1420
1421
1422
1423
1424
1425
1426
1427
1428
1429
1430
1431
1432
1433
1434
1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
1500
1501
1502
1503
1504
1505
1506
1507
1508
1509
1510
1511
1512
1513
1514
1515
1516
1517
1518
1519
1520
1521
1522
1523
1524
1525
1526
1527
1528
1529
1530
1531
1532
1533
1534
1535
1536
1537
1538
1539
1540
1541
1542
1543
1544
1545
1546
1547
1548
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620
1621
1622
1623
1624
1625
1626
1627
1628
1629
1630
1631
1632
1633
1634
1635
1636
1637
1638
1639
1640
1641
1642
1643
1644
1645
1646
1647
1648
1649
1650
1651
1652
1653
1654
1655
1656
1657
1658
1659
1660
1661
1662
1663
1664
1665
1666
1667
1668
1669
1670
1671
1672
1673
1674
1675
1676
1677
1678
1679
1680
1681
1682
1683
1684
1685
1686
1687
1688
1689
1690
1691
1692
1693
1694
1695
1696
1697
1698
1699
1700
1701
1702
1703
1704
1705
1706
1707
1708
1709
1710
1711
1712
1713
1714
1715
1716
1717
1718
1719
1720
1721
1722
1723
1724
1725
1726
1727
1728
1729
1730
1731
1732
1733
1734
1735
1736
1737
1738
1739
1740
1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800
1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860
1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070
2071
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2089
2090
2091
2092
2093
2094
2095
2096
2097
2098
2099
2100
2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215
2216
2217
2218
2219
2220
2221
2222
2223
2224
2225
2226
2227
2228
2229
2230
2231
2232
2233
2234
2235
2236
2237
2238
2239
2240
2241
2242
2243
2244
2245
2246
2247
2248
2249
2250
2251
2252
2253
2254
2255
2256
2257
2258
2259
2260
2261
2262
2263
2264
2265
2266
2267
2268
2269
2270
2271
2272
2273
2274
2275
2276
2277
2278
2279
2280
2281
2282
2283
2284
2285
2286
2287
2288
2289
2290
2291
2292
2293
2294
2295
2296
2297
2298
2299
2300
2301
2302
2303
2304
2305
2306
2307
2308
2309
2310
2311
2312
2313
2314
2315
2316
2317
2318
2319
2320
2321
2322
2323
2324
2325
2326
2327
2328
2329
2330
2331
2332
2333
2334
2335
2336
2337
2338
2339
2340
2341
2342
2343
2344
2345
2346
2347
2348
2349
2350
2351
2352
2353
2354
2355
2356
2357
2358
2359
2360
2361
2362
2363
2364
2365
2366
2367
2368
2369
2370
2371
2372
2373
2374
2375
2376
2377
2378
2379
2380
2381
2382
2383
2384
2385
2386
2387
2388
2389
2390
2391
2392
2393
2394
2395
2396
2397
2398
2399
2400
2401
2402
2403
2404
2405
2406
2407
2408
2409
2410
2411
2412
2413
2414
2415
2416
2417
2418
2419
2420
2421
2422
2423
2424
2425
2426
2427
2428
2429
2430
2431
2432
2433
2434
2435
2436
2437
2438
2439
2440
2441
2442
2443
2444
2445
2446
2447
2448
2449
2450
2451
2452
2453
2454
2455
2456
2457
2458
2459
2460
2461
2462
2463
2464
2465
2466
2467
2468
2469
2470
2471
2472
2473
2474
2475
2476
2477
2478
2479
2480
2481
2482
2483
2484
2485
2486
2487
2488
2489
2490
2491
2492
2493
2494
2495
2496
2497
2498
2499
2500
2501
2502
2503
2504
2505
2506
2507
2508
2509
2510
2511
2512
2513
2514
2515
2516
2517
2518
2519
2520
2521
2522
2523
2524
2525
2526
2527
2528
2529
2530
2531
2532
2533
2534
2535
2536
2537
2538
2539
2540
2541
2542
2543
2544
2545
2546
2547
2548
2549
2550
2551
2552
2553
2554
2555
2556
2557
2558
2559
2560
2561
2562
2563
2564
2565
2566
2567
2568
2569
2570
2571
2572
2573
2574
2575
2576
2577
2578
2579
2580
2581
2582
2583
2584
2585
2586
2587
2588
2589
2590
2591
2592
2593
2594
2595
2596
2597
2598
2599
2600
2601
2602
2603
2604
2605
2606
2607
2608
2609
2610
2611
2612
2613
2614
2615
2616
2617
2618
2619
2620
2621
2622
2623
2624
2625
2626
2627
2628
2629
2630
2631
2632
2633
2634
2635
2636
2637
2638
2639
2640
2641
2642
2643
2644
2645
2646
2647
2648
2649
2650
2651
2652
2653
2654
2655
2656
2657
2658
2659
2660
2661
2662
2663
2664
2665
2666
2667
2668
2669
2670
2671
2672
2673
2674
2675
2676
2677
2678
2679
2680
2681
2682
2683
2684
2685
2686
2687
2688
2689
2690
2691
2692
2693
2694
2695
2696
2697
2698
2699
2700
2701
2702
2703
2704
2705
2706
2707
2708
2709
2710
2711
2712
2713
2714
2715
2716
2717
2718
2719
2720
2721
2722
2723
2724
2725
2726
2727
2728
2729
2730
2731
2732
2733
2734
2735
2736
2737
2738
2739
2740
2741
2742
2743
2744
2745
2746
27
```



```

187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208

```

30		R(I,J) = TMP1(I,J)
40		IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
50		CONTINUE
	60	DO 60 I = 1,N
		IF(ABS(NUMR(I)) .GT. EPS) GOTO 22
	60	CONTINUE
	22	INUM = 0
		DO 70 J = 1,N
		INUM = INUM + 1
		NUMR(INUM) = NUMR(J)
	70	CONTINUE
		RETURN
		END
		FUNCTION TRACE(A,IA,N)
		REAL A(5,5)
		TRACE=0.0
		DO 56 I=1,N
		TRACE=TRACE+A(I,I)
	56	CONTINUE
		RETURN
		END

THE TRANSFER FUNCTION WR/WR* USING PI CONTROLLER

FREQ	SLIP	CUR	G1	G2	T2
50.0000	0.0030	60.0000	1.3000	1.0000	0.1000

THE MATRIX [A11] IS

-1.0000	0.0000	4.6167	0.0000
0.0000	0.0408	0.0150	0.0000
0.0000	-0.0150	0.0408	0.0000
0.0000	0.0000	2.9167	-1.0000

THE MATRIX [B] IS

-8.5144
0.0000
0.9163
0.0000

VOLTAGE	THE STEADY STATE OPERATING POINT IS		
	IDRO	IDRO	TORQUE
165.14	-7.28	19.78	57.70

THE MATRIX [A] IS

-147.3790	3.8843	-474.8097	134.1032	-43.3984
136.0165	-6.1472	437.2607	-123.7642	59.8348
0.8698	0.9425	-2.5623	0.0000	-53.7826
0.0000	0.0000	0.0000	0.0000	-1.0000
5.6266	0.0000	18.8174	0.0000	0.0000

THE MATRIX [B] IS

13.4103
-12.3764
0.0000
1.0000
0.0000

THE MATRIX [C] IS

0 0 0 0 0 1.1

THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC

75.453942
1141.218200
4991.639500
11248.559000

THE COEF OF THE DEN IN THE TRANSFER FUNC

1.000000

156.088500

2028.145800

15076.242000

16158.606000

11248.716000

THE POLES OF THE MATRIX LAJ ARE

-142.6019	0.0000
-6.1774	7.2051
-6.1774	-7.2051
-0.5659	0.7453
-0.5659	-0.7453

THE POLES OF THE TRANSFER FUNCTION ARE

-142.6019	0.0000
-6.1774	-7.2051
-6.1774	7.2051
-0.5659	-0.7453
-0.5659	0.7453

THE ZEROS OF THE TRANSFER FUNCTION ARE

-10.0000	0.0000
-2.5623	-2.8883
-2.5623	2.8883

C
C
C
C
C

C

97

95

94

96

92

93

C

12

13

14

15

C

19

16

17

C

C

4

THIS PROGRAM GETS THE TRANSFER FUNCTIONS WR/WR*, WR/WSL
WITH INDEPENDENT SPEED AND SLIP FREQUENCY CONTROL USING
PROPORTIONAL PLUS INTEGRAL (PI) CONTROLLER. IT DETERMINES THE
POLES AND ZEROES OF THE ABOVE TRANSFER FUNCTIONS.

DIMENSION A(5,5),WKSPCE(4),E(4,4),G(4,1),D(4,1)
DIMENSION RR(5),RI(5),AA(4,4),BB(4,1),B(5,1)
DIMENSION Z(1),INTEGE(5),C(1,5),NUMR(6),DEN(6)
DIMENSION REZ(5),IMZ(5),RZ(5),I2(5),H(5,5)

REAL L1,L2
OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
READ(40,*) ((G(IB,M),IB=1,4),M=1,1)

IA=5;IB=5;IC=1;N=5
FQ=50;CIR=60;S=0.02;L1=1.3;T2=0.1

READ(05,*) FQ,S,CIR,L1,L2,T2

READ(05,*) L2

WRITE(05,*) FQ,S,CIR,L1,L2,T2

WRITE(41,97)

FORMAT(1X,////////)

WRITE(41,95)

FORMAT(10X, '*****',/)

WRITE(41,94)

FORMAT(10X, 'THE TRANSFER FUNCTION WR/WR* USING PI CONTROLLER',/)

WRITE(41,96)

FORMAT(10X, '*****',/)

WRITE(41,92)

FORMAT(10X, 'FREQ',6X,'SLIP',6X,'CUR',6X,'G1',8X,'G2',8X,'T2',/)

WRITE(41,93) FQ,S,CIR,L1,L2,T2

FORMAT(5X,6F10.4,/))

CQS=1.10266*CIR; P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31

RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB

FL=5.5/WB;RF=0.91;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1

R1=RS+RF1;CL=(F*RL-CM*CM);WR=WE-S*WE;WSL=WE-WR

E(1,3)=CM*WE; E(2,3)=RL*S*WE

E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS

G(1,1)=-R1*CQS; G(3,1)=CM*S*CQS*WE

*****THE EQUATION IS [A11][X]=[B]*****

WRITE(41,12)

FORMAT(20X, 'THE MATRIX [A11] IS',/)

WRITE(41,13) ((E(IA,N),N=1,4),IA=1,4)

FORMAT(10X,4F10.4/)

WRITE(41,14)

FORMAT(20X, 'THE MATRIX [B] IS',/)

WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)

FORMAT(10X,1F10.4/)

*****FINDS STEADY STATE OPERATING POINT *****

WRITE(41,19)

FORMAT(7(15X, 'THE STEADY STATE OPERATING POINT IS'))

CALL FQ4AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)

O(1,1)=1.654*D(1,1)

WRITE(41,16)

FORMAT(4X, 'VOLTAGE',4X,'IQRD',8X,'IDRD',5X,'TORQUE',/)

WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)

FORMAT(1X,4F10.2)

R=R1+L1

R=R1

A(1,1)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL

A(1,4)=L1*RL/CL;A(1,5)=-((CM*RL*D(3,1)/CL)-(L1*L2*T2*RL)/CL

A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL;A(2,4)=-L1*CM/CL

A(2,3)=RL*F+WR/CL-WE;A(2,5)=(CM*CM*D(3,1)/CL)+L1*L2*T2*CM/CL

A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL;A(3,4)=0

A(3,5)=0

A(3,4)=-(CM*CQS+RL*D(2,1))/RL

A(4,1)=0;A(4,2)=0;A(4,3)=0;A(4,4)=0;A(4,5)=-L2

A(5,1)=3*P*P*CM*D(3,1)/(B*RJ);A(5,2)=0

A(5,3)=(3*P*P*CM*CQS)/(B*RJ);A(5,4)=0;A(5,5)=0

DO 3 I=1,5

DO 4 J=1,5

H(1,J)=A(1,J)

CONTINUE


```

095 3 CONTINUE
096 WRITE(41,73)
097 73 FORMAT(/(20X,'THE MATRIX [A] IS'),/)
098 WRITE(41,74) ((A(N,K),K=1,5),N=1,5)
099 74 FORMAT(1X,5F14.4,/)
100 C B(1,1)=L1*RL/CL;B(2,1)=-L1*CM/CL;B(3,1)=0;B(4,1)=0
101 C B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
102 C B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*CMS+RL*D(2,1))/RL;B(4,1)=0
103 C B(5,1)=0
104 B(1,1)=L1*L2*T2*RL/CL;B(2,1)=-L1*L2*T2*CM/CL;B(3,1)=0
105 B(4,1)=L2;B(5,1)=0
106 WRITE(41,21)
107 21 FORMAT(/(20X,'THE MATRIX [B] IS'),/)
108 WRITE(41,38) ((B(N,K),K=1,1),N=1,5)
109 38 FORMAT(10X,5F16.4,/)
110 C C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=0;C(1,5)=1
111 C C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
112 23 WRITE(41,23)
113 23 FORMAT(20X,'THE MATRIX [C] IS'),/)
114 WRITE(41,24) ((C(N,K),K=1,5),N=1,1)
115 24 FORMAT(20X,1F5.1,/)
116 CALL SSP2TF(A,5,B,5,C,1,5,NUMR,DEN,INUM,IFAIL)
117 WRITE(41,31)
118 31 FORMAT(/(10X,'THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC'),/)
119 WRITE(41,11) (NUMR(I),I=1,INUM)
120 98 WRITE(41,98)
121 98 FORMAT(1X,2(/////////))
122 WRITE(41,32)
123 32 FORMAT(/(10X,'THE COEF OF THE DEN IN THE TRANSFER FUNC'),/)
124 WRITE(41,11) (DEN(I),I=1,5)
125 11 FORMAT(1X,5F15.6,/)
126 CALL F02AEF(H,5,5,RR,RI,INTEGE,0)
127 WRITE(41,81)
128 81 FORMAT(/(10X,'THE POLES OF THE MATRIX [A] ARE'),/)
129 WRITE(41,83) (RR(N),RI(N),N=1,5)
130 83 FORMAT(10X,2F16.4)
131 CALL C02AEF(DEN,6,REZ,IMZ,TOL,0)
132 WRITE(41,75)
133 75 FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE'),/)
134 WRITE(41,76) (REZ(N),IMZ(N),N=1,5)
135 76 FORMAT(10X,2F16.4)
136 CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
137 WRITE(41,77)
138 77 FORMAT(/(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE'),/)
139 WRITE(41,78) (RZ(I),IZ(I),I=1,3)
140 78 FORMAT(10X,2F16.4)
141 STOP
142 END
143 *****
144 C THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF NUM & DEN
145 C OF THE TRANSFER FUNCTION.
146 C *****
147 C SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
148 REAL NUMR(6),DEN(6)
149 REAL A(5,5),B(5,1),C(1,5),TMP1(5,5),TMP2(1,1),R(5,5)
150 DATA EPS/0.000001/
151 IFAIL = 1
152 IF( N .LE. 0 ) RETURN
153 IFAIL = 2
154 DO 10 I = 1,N
155 IF(B(I,1) .NE. 0.0) GOTO 36
156 10 CONTINUE
157 RETURN
158 36 DO 20 I = 1,N
159 DO 20 J = 1,N
160 R(I,J) = 0.0
161 R(I,I) = 1.0
162 20 CONTINUE
163 DEN(1) = 1.0
164 DO 50 K = 1,N
165 CALL F01CKF(TMP1,R,B,5,5,5,Z,1,1,0)
166 CALL F01CKF(TMP2,C,TMP1,1,1,5,2,1,1,0)
167 NUMR(K) = TMP2(1,1)
168 CALL F01CKF(TMP1,A,B,5,5,5,Z,1,1,0)
169 ALPHAK = -TRACE(TMP1,5,5)/K
170 DEN(K+1) = ALPHAK
171
172
173
174
175
176
177
178

```

```

DO 40 I = 1,N
  DO 30 J = 1,N
    R(I,J) = TMP1(I,J)
  IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
  CONTINUE
CONTINUE
DO 60 I = 1,N
  IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
CONTINUE
INUM = 0
DO 70 J = 1,N
  INUM = INUM + 1
  NUMR(INUM) = NUMR(J)
CONTINUE
RETURN
END
FUNCTION TRACE(A,IA,N)
REAL A(5,5)
TRACE=0.0
DO 56 I=1,N
  TRACE=TRACE+A(I,1)
CONTINUE
RETURN
END

```

30

40

50

60

22

70

56

 THE TRANSFER FUNCTION WR/WR* USING PI CONTROLLER

FREQ	SLIP	CUR	G1	G2	T2
50.0000	0.0030	60.0000	1.3000	1.0000	0.1000

THE MATRIX [A11] IS

-1.0000	0.0000	4.6167	0.0000
0.0000	0.0408	0.0150	0.0000
0.0000	-0.0150	0.0408	0.0000
0.0000	0.0000	2.9167	-1.0000

THE MATRIX [B] IS

-8.5144
0.0000
0.9163
0.0000

VOLTAGE	THE STEADY STATE OPERATING POINT IS		
	I0R0	I0R0	TORQUE
165.14	-7.28	19.78	57.70

THE MATRIX [A] IS

-147.3790	3.8843	-474.8097	134.1032	-43.3984
136.0165	-6.1472	437.2607	-123.7642	40.0525
0.8698	0.9425	-2.5623	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	-1.0000
5.6266	0.0000	18.8174	0.0000	0.0000

THE MATRIX [B] IS

13.4103
-12.3764
0.0000
1.0000
0.0000

THE MATRIX [C] IS

0.	0.	0.	0.	1.
----	----	----	----	----

THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC

75.453942
1141.218200
4991.639300
11248.537000

THE COEF OF THE DEN IN THE TRANSFER FUNC

1.000000

156.088500

1016.096200

4165.882400

7507.040200

11247.378000

THE POLES OF THE MATRIX [A] ARE

-149.4750	0.0000
-2.4854	2.7959
-2.4854	-2.7959
-0.8214	2.1686
-0.8214	-2.1686

THE POLES OF THE TRANSFER FUNCTION ARE

-149.4750	0.0000
-2.4852	-2.7959
-2.4852	2.7959
-0.8215	-2.1685
-0.8215	2.1685

THE ZEROS OF THE TRANSFER FUNCTION ARE

-10.0600	0.0000
-2.5623	-2.8883
-2.5623	2.8883


```

095
096
097
098
099
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
13
14
15
19
16
17
73
74
21
38
23
24
31
32
11
81
84
75
76
77
78
56
53
57
54
58
55
1
2
5
C
C
C
C
10

```

```

FORMAT(10X,4F10.4/)
WRITE(41,14)
FORMAT(10X, 'THE MATRIX [B11] IS',/)
WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
FORMAT(10X,4F10.4/)
WRITE(41,19)
FORMAT(15X, 'THE STEADY STATE OPERATING POINT IS')
WRITE(41,16)
FORMAT(4X, 'VOLTAGE',4X, 'IDRO',8X, 'IDRO',5X, 'TORQUE',/)
WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
FORMAT(1X,4F10.2)
WRITE(41,73)
FORMAT(20X, 'THE MATRIX [A] IS',/)
WRITE(41,74) ((A(N,K),K=1,4),N=1,4)
FORMAT(10X,4F16.4/)
WRITE(41,21)
FORMAT(20X, 'THE MATRIX [B] IS',/)
WRITE(41,38) ((B(N,K),K=1,1),N=1,4)
FORMAT(10X,4F16.4/)
WRITE(41,23)
FORMAT(20X, 'THE MATRIX [C] IS',/)
WRITE(41,24) ((C(N,K),K=1,4),N=1,1)
FORMAT(20X, ' [4F4.1]',/)
CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
WRITE(41,31)
FORMAT(10X, 'THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC',/)
WRITE(41,11) (NUMR(I),I=1,INUM)
WRITE(41,32)
FORMAT(10X, 'THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
WRITE(41,11) (DEN(I),I=1,5)
FORMAT(7(1X,5F15.6))
CALL ROUTH(PQ,WSL,L1,C1,E,G,D,A,H,B,C,D3,D4,H3,H4,D1)
CALL POZAFF(H,4,4,RR,RI,INTEGE,0)
WRITE(41,81)
FORMAT(10X, 'THE POLES OF THE MATRIX [A] ARE',/)
WRITE(41,84) (RR(N),RI(N),N=1,4)
FORMAT(10X,2F16.4)
CALL COZAEF(DEN,5,REZ,IMZ,TOL,0)
WRITE(41,75)
FORMAT(10X, 'THE POLES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
FORMAT(10X,2F16.4)
CALL COZAEF(NUMR,INUM,RZ,IZ,TOL,0)
WRITE(41,77)
FORMAT(10X, 'THE ZEROS OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,78) (RZ(I),IZ(I),I=1,4)
FORMAT(10X,2F16.4)
WRITE(41,56)
FORMAT(1X, 'THE MATRIX [D3] IS',/)
WRITE(41,53) ((H3(N,K),K=1,3),N=1,3)
FORMAT(1X,3F14.4/)
WRITE(41,57)
FORMAT(1X, 'THE MATRIX [D4] IS',/)
WRITE(41,54) ((H4(N,K),K=1,4),N=1,4)
FORMAT(1X,4F14.4/)
WRITE(41,58)
FORMAT(1X, 'THE VALUES OF DETERMINANTS D1--D4 ARE',/)
WRITE(41,55) (D1(N),N=1,4)
FORMAT(1X,4F25.4)
CONTINUE
CONTINUE
CONTINUE
STOP
END
*****
THIS SUBROUTINE DETERMINES THE TRANSFER FUNCTION FOR THE
GIVEN [A], [B] AND [C] USING THE LEVRIER-PADDEEV METHOD
*****
SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
READ NUMR(5),DEN(5)
READ A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
DATA EPS/0.000001/
IFAIL = 1
IF( N .LE. 0 ) RETURN
IFAIL = 2
DO 10 I = 1,N
  IF(B(I,1) .NE. 0.0) GOTO 36
CONTINUE
RETURN

```

184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267

36

20

30

40

50

60

22

70

50

C

C

C

C

C

4

3

C

C

```
DO 20 I = 1,N
DO 20 J = 1,N
  R(I,J) = 0.0
  R(I,I) = 1.0
CONTINUE
DEN(1) = 1.0
DO 50 K = 1,N
  CALL FO1CKF(TMP1,R,B,4,4,4,Z,1,1,0)
  CALL FO1CKF(TMP2,C,TMP1,1,1,4,Z,1,1,0)
  NUMR(K) = TMP2(1,1)
  CALL FO1CKF(TMP1,A,K,4,4,4,Z,1,1,0)
  ALPHAK = -TRACE(TMP1,4,4)/K
  DEN(K+1) = ALPHAK
DO 40 I = 1,N
DO 30 J = 1,N
  R(I,J) = TMP1(I,J)
IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
CONTINUE
CONTINUE
CONTINUE
DO 60 I = 1,N
  IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
CONTINUE
INUM = 0
DO 70 J = 1,N
  INUM = INUM + 1
  NUMR(INUM) = NUMR(J)
CONTINUE
RETURN
END
FUNCTION TRACE(A,IA,N)
REAL A(4,4)
TRACE=0.0
DO 56 I=1,N
  TRACE=TRACE+A(I,I)
CONTINUE
RETURN
END
*****
THIS SUBROUTINE GIVES THE VALUES DETERMINANTS D1,D2,D3 , D4
*****
SUBROUTINE ROUTH(F0,WSL,L1,CIR,E,G,D,A,H,B,C,D3,D4,H3,H4,D1)
DIMENSION AC(4,4),WKSPCE(4),E(4,4),G(4,1),D(4,1)
DIMENSION RR(4),RI(4),AA(4,4),BB(4,1),B(4,1)
DIMENSION Z(1),INTEGE(4),C(1,4),NUMR(5),DEN(5)
DIMENSION REZ(4),IMZ(4),RZ(4),IZ(4),H(4,4)
DIMENSION D1(4),D3(3,3),D4(4,4),H3(3,3),H4(4,4)
REAL C1
C1=1.0266*CIR; P=4.0;WB=60.0*6.2832;WE=6.2832*F0;RJ=0.31
RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
RI=RS+RF1;CL=(F*RL-CM*CM);WR=WE-WSL
E(1,3)=CM*WE; E(2,3)=RL*WSL
E(3,2)=-RL*WSL; E(4,3)=0.75*P*CM*WSL
G(1,1)=-P1*CM; G(3,1)=CM*CM*WSL
*****THE EQUATION IS [A111(X)]=[B1]*****
*****FINDS STEADY STATE OPERATING POINT *****
CALL FO4AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
D(1,1)=1.654*D(1,1)
R=RI+CL
A(1,1)=-(RI+R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
A(1,4)=-CM*RL*D(3,1)/CL;A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL
A(2,3)=RL*F*WR/CL;A(2,4)=(CM*F*D(3,1)/CL)
A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL
A(3,4)=-(CM*CM*WSL*D(2,1))/RL
R(4,1)=3*P*P*CM*D(3,1)/(B*RJ);A(4,2)=0
A(4,3)=(3*P*P*CM*CM*WSL)/(B*RJ);A(4,4)=0
DO 3 I=1,N
DO 4 J=1,N
  H(I,J)=A(I,J)
CONTINUE
CONTINUE
B(1,1)=L1*RL/CL;B(2,1)=-L1*CM/CL;B(3,1)=0;B(4,1)=0
B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*CM*WSL+RL*D(2,1))/RL
B(4,1)
```

103077

9307